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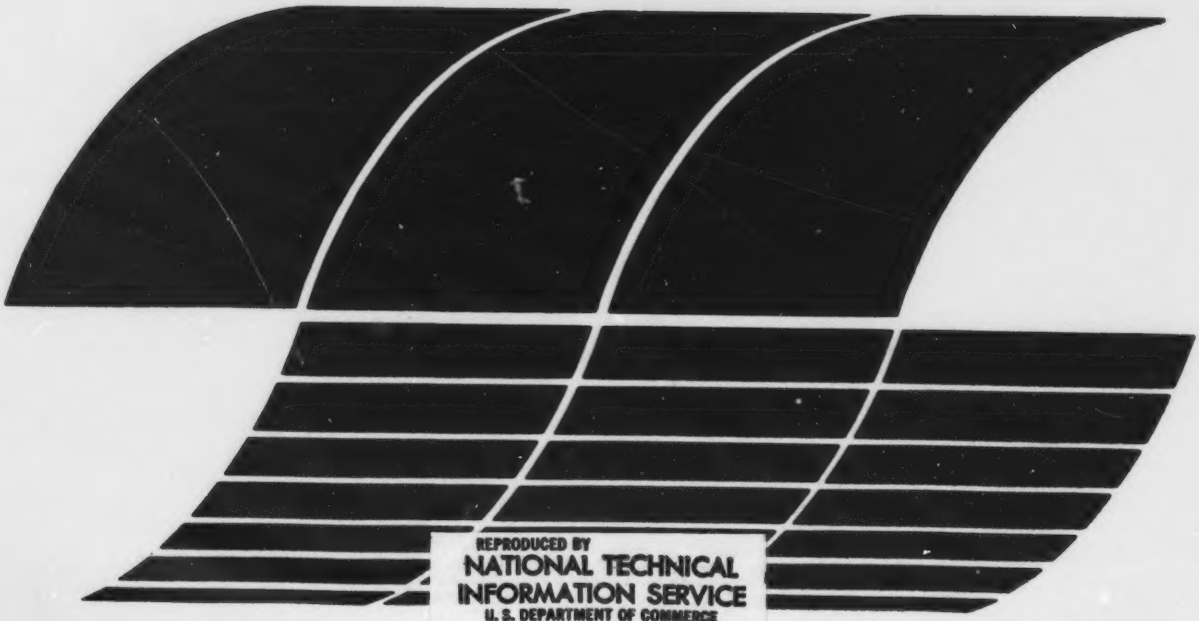

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16. ABSTRACT The report gives results of advanced testing (late-November 1976 - June 1978) of 30,000-35,000 acfm (10 MW equivalent) lime/limestone wet scrubbers for SO_2 and particulate removal at TVA's Shawnee power station. Forced oxidation with two scrubber loops was developed on the venturi/spray tower system with limestone, lime, and limestone/MgO slurries. Bleed stream oxidation was successful only with limestone/MgO slurry. Forced oxidation with a single scrubber loop was developed on the TCA system with limestone slurry. Other test blocks on the TCA were limestone with low fly ash loadings, limestone type and grind, automatic limestone feed control, limestone reliability, limestone with Ceilcote egg-crate type packing, lime/MgO, and flue characterization.

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ABSTRACT

This Fourth Progress Report presents the test results from late-November 1976 through June 1978 of the Advanced Test Program on a prototype lime/limestone wet-scrubbing test facility for removing SO_2 and particulates from coal-fired boiler flue gases. The test facility is located at TVA's Shawnee Power Station, Paducah, Kentucky. Tests were conducted on two parallel scrubber systems: a venturi/spray tower (35,000 acfm @ 300°F), and a Turbulent Contact Absorber or TCA (30,000 acfm @ 300°F).

Forced oxidation with two scrubber loops was developed for the venturi/spray tower system. This system was successfully demonstrated with limestone, lime, and limestone/MgO slurries. An open pipe air sparger discharging into an agitated tank was successfully used to oxidize the slurry. Oxidized slurry solids have improved dewatering and handling properties.

Attempts to oxidize the venturi/spray tower bleed stream were successful only when magnesium ion was present to buffer the slurry pH and to increase the liquor sulfite concentration for oxidation.

Forced oxidation with limestone slurry in a single scrubber loop was demonstrated on the TCA system. In this system, more efficient oxidation was achieved with an air sparger than with an eductor.

Additional testing on the TCA system included limestone testing with low fly ash loadings, limestone type and grind testing, automatic limestone feed control testing, limestone reliability testing with high fly ash loadings, limestone testing with Ceilcote egg-crate type packing, lime and limestone testing with added MgO, and flue gas characterization testing to determine inlet and outlet particulate mass loadings, size distribution, and SO_3 concentration.

Auxiliary studies during this test period included laboratory reactivity studies of various limestone types and grinds, development of pressure drop correlations for both scrubbers, trace element analyses in the slurry liquor, and waste solids dewatering and characterization studies.

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Section 1
SUMMARY

This is the fourth progress report on an Advanced Test Program under the sponsorship of the Environmental Protection Agency (EPA) to test prototype lime and limestone wet-scrubbing systems for removing sulfur dioxide (SO_2) and particulate matter from coal-fired utility boiler flue gases. Test results during the period from late-November 1976 through June 1978 are presented in this report. Results of earlier testing have been published in EPA report Nos. EPA-650/2-75-047 (June 1975), EPA-600/2-75-050 (September 1975), EPA-600/7-76-008 (September 1976), and EPA-600/7-77-105 (September 1977). The program is being conducted at a test facility operating on flue gas from Boiler No. 10 at the Tennessee Valley Authority (TVA) Shawnee Power Station, Paducah, Kentucky. Bechtel National, Inc. of San Francisco is the major contractor and test director, and TVA is the constructor and facility operator.

There are two parallel scrubbing systems being operated during the Advanced Test Program:

- A venturi followed by a spray tower
- A Turbulent Contact Absorber (TCA)

Each system is capable of treating approximately 10 MW equivalent (maximum rates of 35,000 acfm* @ 300°F for the venturi/spray tower and 30,000 acfm @ 300°F for the TCA) of flue gas normally containing 1500 to 4500 ppm of SO_2.

Flue gas can be withdrawn from either the upstream or downstream side of the Boiler No. 10 particulate removal equipment, allowing testing with either high fly ash loadings (3 to 6 grains/dry scf) or low fly ash loadings (0.04 to 0.2 grain/dry scf).

Major areas of testing during this reporting period were:

- Two-scrubber-loop forced-oxidation testing on the venturi/spray tower system with the following alkalis:
    - Limestone slurry, high and low fly ash loadings in the flue gas
    - Limestone slurry with added magnesium oxide (MgO), high fly ash loadings in the flue gas
    - Lime slurry, high and low fly ash loadings in the flue gas
- Bleed stream oxidation testing on the venturi/spray tower with limestone slurry and added MgO and with high fly ash loadings in the flue gas
- Limestone testing on the TCA with low fly ash loadings in the flue gas
- Limestone type and grind testing on the TCA
- Automatic limestone feed control testing on the TCA
- One-scrubber-loop forced-oxidation testing using an air eductor on the TCA with limestone slurry and with high fly ash loadings in the flue gas

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* Although it is the policy of the EPA to use the metric system for quantitative descriptions, the British system is used in this report. Readers who are more accustomed to metric units are referred to the conversion table in Appendix A.

- Limestone reliability testing on the TCA with high fly ash loadings in the flue gas
- Limestone testing with Ceilcote egg-crate type plate packing on the TCA
- One-scrubber-loop forced-oxidation testing using an air sparger on the TCA with limestone slurry and with high fly loadings in the flue gas
- Limestone testing on the TCA with added MgO and with high fly ash loadings in the flue gas
- Lime testing on the TCA with added MgO and with high fly ash loadings in the flue gas
- Flue gas characterization testing on both scrubber systems to determine inlet and outlet particulate mass loadings, size distribution, and SO_3 concentrations

In addition to the major tasks of testing listed above, auxiliary studies were conducted in the following areas:

- Laboratory studies of the reactivity of various limestone types and grinds
- Development of pressure drop correlations for the spray tower and the TCA
- Analysis of trace elements in the slurry liquor which may catalyze or inhibit the oxidation of sulfite
- Waste solids dewatering and characterization studies

Major conclusions obtained from the work during the reporting period are summarized below.

1.1 TWO-SCRUBBER-LOOP FORCED-OXIDATION TEST RESULTS ON THE VENTURI/SPRAY TOWER SYSTEM

Following the development of forced-oxidation techniques at the EPA IERL-RTP pilot plant on a 0.1-MW scale, forced oxidation had been successfully demonstrated at the Shawnee Test Facility on 10-MW prototype scrubbers. From early January 1977 through mid-May 1978, the venturi/spray tower system was operated in a two-scrubber-loop configuration with forced oxidation of calcium sulfite to calcium sulfate in the low-pH, venturi slurry loop (the first of two independent slurry recirculation loops). A total of 23 runs were made with limestone slurry (see Section 5), including 15 runs with high fly ash loadings and 8 runs with low fly ash loadings in the flue gas. Twenty runs were made with lime slurry (see Section 7), including 10 runs each with high and low fly ash loadings. And finally, 6 runs were made using limestone slurry with added MgO (see Section 6), all with high fly ash loadings in the flue gas.

A summary of results of these runs follows:

- Forced oxidation of sulfite to sulfate in the first of two independent scrubbing loops was successfully demonstrated in the two-scrubber-loop venturi/spray tower system with both lime and limestone slurries. Successful demonstration was culminated with a lime and a limestone one-month reliability test, both using flue gas with high fly ash loadings.

- The operating characteristics and test results for lime and limestone are similar in many aspects. Under the one-month reliability test conditions of 18,000 to 35,000 acfm gas rate, 600 gpm venturi slurry rate, 1600 gpm spray tower slurry rate, 15 percent venturi slurry solids concentration, 18 ft oxidation tank level, and 5.5 oxidation tank pH, both the lime and limestone runs achieved 97 percent or higher average sulfite oxidation at air stoichiometric ratios ranging from 1.4 to 2.8 atoms oxygen/mole SO_2 absorbed. The filter cake solids content averaged 85 percent or higher.

- For both lime and limestone tests, ranges of conditions under which near complete sulfite oxidation (greater than 95 percent) was demonstrated were an oxidation tank pH.of 4.5 to 5.5, an oxidation tank level of at least 14 ft, and an air stoichiometry of at least 1.5 atoms oxygen/mole SO_2 absorbed. Filter cake solids contents of 80 percent or greater were consistently achieved under these conditions.

- Slurries with high or low fly ash loadings oxidized equally well.

- Sulfite oxidation of 90 percent or higher was required to obtain maximum improvement in waste solids dewatering characteristics.

- In a lime test, the degree of sulfite oxidation was not affected when the venturi slurry solids concentration was decreased from the normal 15 percent to 8 percent.

- For lime slurry, oxidation efficiency appeared to drop off at pH's greater than 6. Limestone slurry normally has pH values below 6.

- Forced oxidation was achieved by simple air/slurry contact in the oxidation tank. Within the ranges of test conditions, air/slurry contact efficiency did not appear to be affected by using an air sparger with 130 1/8-inch holes, an air sparger with 40 1/4-inch holes, or a 3-inch diameter open pipe was used. Air/slurry contact was primarily achieved by the two-turbine agitator operated at 56 rpm and rated at 17 brake Hp.

- Independent lime addition to both scrubber loops was necessary to have smooth venturi and spray tower inlet pH control. With limestone operation, addition of fresh limestone slurry to the spray tower hold tank alone was sufficient to maintain the venturi inlet pH at the desired level.

- In both lime and limestone operations, the venturi inlet slurry liquor constantly exhibited a gypsum saturation level of about 100 percent when oxidation was forced within the venturi loop. This was probably the result of the abundance of gypsum crystal seeds produced by forced oxidation. The 100 percent saturation level is well below the incipient scaling level of 135 percent.

- In a limestone run operating without a gypsum desupersaturation tank after the oxidation tank, neither sulfite oxidation nor gypsum saturation in the venturi loop was adversely affected.

- Lime utilization in the spray tower averaged about 88 percent. Overall lime utilization averaged 98 percent, demonstrating the advantage of a two-scrubber-loop system.

- Limestone utilization was improved with the two-scrubber-loop operation to at least 80 percent and as high as 98 percent, depending on the venturi inlet pH which averaged from 4.5 to 5.5.

- In a limestone test, operation with the agitator turned off in the oxidation tank was not successful. Air sparging alone in the oxidation tank could not keep the solids from settling.

- In a series of lime tests, oxidation efficiency did not appear to be affected when the oxidation tank level was dropped from 18 ft to 14 ft at 1.8 air stoichiometry and 5.5 pH. At a 10-ft tank level, an air stoichiometry approaching 4 atoms oxygen/mole

SO_2 absorbed was required to achieve near complete oxidation.

- Spray tower scaling (mostly by calcium sulfite) may result when the recirculated slurry solids concentration in the spray tower drops below about 7 percent (low fly ash loading). This is especially true for lime operation when the spray tower outlet pH stays above about 5.5. A low slurry solids concentration in the spray tower also penalizes SO_2 removal efficiency in limestone scrubbing because of the reduced dissolved alkali concentration.

- The anticipated SO_2 removal enhancement was achieved in the two-scrubber-loop venturi/spray tower limestone system by adding MgO in the spray tower slurry loop. Under typical operating conditions, average SO_2 removal was 96 percent at 2250 ppm average inlet SO_2 concentration with 5150 ppm effective magnesium ion concentration* in the spray tower. Under the same operating conditions but without MgO addition, SO_2 removal averaged 86 percent at 2550 ppm inlet SO_2 concentration.

- Magnesium ion does not enhance SO_2 removal in a scrubber loop in which oxidation is forced, because sulfite ion is oxidized into nonscrubbing sulfate ion. SO_2 removal in the venturi loop (oxidation loop) was determined in a run with MgO addition to be 29 percent, which is typical of removal efficiency with limestone slurry in the absence of magnesium ion.

- The oxidation efficiency appeared to be unaffected, if not improved, by the presence of magnesium ion.

- For runs with MgO addition (8000 ppm effective magnesium ion in the bleed slurry liquor), filter cake solids content averaged 85 percent at 98 percent oxidation, essentially the same as that without MgO addition.

1.2 BLEED STREAM OXIDATION TEST RESULTS ON THE VENTURI/SPRAY TOWER SYSTEM

From mid-May 1978 through mid-June 1978, four runs were made on the venturi/spray tower system (see Section 8) in which one hold tank was used for both the venturi and spray tower recirculation slurries. The system bleed slurry was taken from the hold tank and sent to a separate tank in which oxidation was forced by simple air/slurry contact. Limestone slurry with high fly ash loading was used in all four runs. Magnesium oxide was added to the effluent hold tank to maintain an effective magnesium ion concentration of 5000 ppm.

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* Effective magnesium ion concentration is defined as the total magnesium ion minus that magnesium ion concentration equivalent to total chlorides. Magnesium chloride has no effect on SO_2 removal.

Major conclusions from these runs were as follows:

- Forced oxidation on the bleed stream outside the scrubber slurry loop is not expected to work with lime or limestone slurries (without added MgO). Slurry pH rise in the oxidation tank, caused by the dissolution of residual alkali, prevents solid calcium sulfite from dissolving and oxidizing in the liquid phase. The pH rise also reduces the rate of oxidation reaction.
- Bleed stream oxidation of limestone slurry is feasible in the presence of a sufficient quantity of magnesium ion. Magnesium ion tends to buffer the pH rise and promotes the availability of dissolved sulfite for oxidation. Higher liquor sulfite concentration also allows the oxidation to take place at a higher pH.
- Average sulfite oxidations greater than 95 percent were achieved with an air stoichiometry of 1.6 atoms oxygen/mole SO_2 absorbed, an oxidation tank level of 18 ft, an oxidation tank pH of 5.4 to 6.3, and 5000 ppm effective magnesium ion concentration. Oxidation was consistently high even though the pH rose as high as 6.7.
- Oxidized slurry from all runs had good dewatering properties. Filter cake solids concentration averaged about 84 percent.
- Oxidation of the bleed stream outside of the scrubber slurry loop did not interfere with the SO_2 removal enhancement by the magnesium ion, as was experienced when oxidation was accomplished within the scrubber loop.
- In two runs, 30 gpm of oxidized slurry was recycled from the oxidation tank back to the effluent hold tank in an attempt to reduce the pH rise in the oxidation tank. This recycle stream proved to be unnecessary as the oxidation tank pH was only 0.1 to 0.2 pH unit higher than the effluent hold tank pH without the recycle.

Additional testing has been planned in the future to fully characterize the limestone/MgO bleed stream oxidation system. The possibility of bleed stream oxidation on a lime/MgO system will also be investigated.

1.3 LIMESTONE TEST RESULTS ON THE TCA WITH LOW FLY ASH LOADINGS IN FLUE GAS

Six limestone runs were conducted on the TCA system from late November 1976 through early February 1977 (see Section 9). All runs were made with flue gas having low fly ash loadings. The main objective of this series of tests was to compare the TCA performances for runs with high and low fly ash loadings. Another objective was to investigate the scrubber inlet slurry pH and SO_2 removal, at low fly ash loading, as functions of the slurry solids concentration, hold tank residence time, number of hold tanks, and limestone stoichiometry. A summary of results of these runs follows.

- At the same limestone utilization, the scrubber inlet pH for runs with low fly ash loadings tended to be 0.3 to 0.4 pH unit higher than runs with high fly ash loadings. This is consistent with earlier observation during venturi/spray tower lime tests. In those tests, at a controlled scrubber inlet pH of 8, lime utilization averaged about 93 percent for runs with low fly ash loadings, compared with about 88 percent for runs with high fly ash loadings. This difference was believed to be caused by the acidic fly ash which releases its acidity from absorbed SO_3 under scrubber conditions, even though the fly ash pond liquor at Shawnee is alkaline after a prolonged period of leaching.

- Within the range of slurry solids concentrations tested (8 to 15 percent), higher solids concentration gave slightly higher scrubber inlet pH and SO_2 removal. The effect is more pronounced at higher residence time (12 minutes) with three tanks in series.

- At the same limestone stoichiometry (1.1) and total residence time (12 minutes), three hold tanks in series gave higher SO_2 removal and scrubber inlet pH than a single hold tank.

1.4 LIMESTONE TYPE AND GRIND TEST RESULTS ON THE TCA SYSTEM

A series of six tests were conducted on the TCA system from March 4 through April 2, 1977 (see Section 10), to compare the reactivity of limestones from two different sources: Fredonia, Kentucky, and Long View, Alabama. The effect of ground limestone size was also investigated. All tests were made with flue gas having high fly ash loadings. Significant findings of these tests follow.

- At the same nominal grind of 70 percent less than 325 mesh, Long View limestone was slightly more reactive than Fredonia limestone. At a residence time of 4.1 minutes, stoichiometric ratio of 1.2 moles Calcium (Ca)/mole SO_2 absorbed, and a liquid-to-gas ratio of 50 gal/Mcf, SO_2 removal was 55 percent at 3350 ppm inlet SO_2 concentration for Long View, compared with 49 percent removal at 3100 ppm inlet SO_2 concentration for Fredonia. However, a severe limestone feed line plugging problem was experienced with the Long View limestone.
- SO_2 removal was sensitive to the limestone grind, especially at a low residence time. At 50 gal/Mcf liquid-to-gas ratio, 1.2 stoichiometric ratio, and 4.1 minutes residence time, SO_2 removal increased from 49 to 72 percent, both at 3100 ppm inlet SO_2, when the grind size of the Fredonia limestone was reduced from 69 percent less than 325 mesh to 96 percent less than 325 mesh. At a higher residence time of 12 minutes, SO_2 removal increased from 54 percent at 3400 ppm inlet SO_2 to only 64 percent at 3250 ppm with the corresponding limestone grinds.

Thus, to obtain the desired degree of SO_2 removal, consideration must be given to the cost trade-off between the use of coarse and fine ground limestone. Use of coarse limestone requires higher limestone stoichiometry, resulting in more waste sludge to be disposed of. Use of fine ground limestone, on the other hand, requires higher capital and operating costs for the ballmills, but lower stoichiometry with less waste sludge generated.

1.5 TEST RESULTS OF AUTOMATIC LIMESTONE FEED CONTROL ON THE TCA SYSTEM

The feasibility of automatic limestone feed control in a limestone wet-scrubbing system was investigated on the TCA from August 30 to September 9, 1977 (see Section 11). The benefits of automatic limestone feed control include:

- Minimizing the limestone usage to meet the SO_2 emission standard
- Reducing manual operation and operator errors
- Reducing the scrubber operating costs
- Improving reliability by reducing the potential for plugging with soft mud-type solids caused by excessive limestone stoichiometry

The control scheme tested at Shawnee was based on the material balance concept. In this scheme, a desired stoichiometric limestone feed is maintained in relation to the amount of SO_2 entering or absorbed in the scrubber according to the following equation:

Limestone (60 percent slurry) addition rate, gpm

= G x (SO2I - Kout) x KSR

where: G = flue gas flow rate, acfm @ 300°F

SO2I = inlet SO_2 concentration measured by Du Pont analyzer, ppm

Kout = a manually adjustable constant related to desired outlet SO_2 concentration, ppm

KSR = a manually adjustable constant proportional to the stoichiometric ratio

= (unit conversion factor) x (stoichiometric ratio)

= 2.34×10^{-8} x (stoichiometric ratio)

The gas rate, G, and inlet SO_2 concentration, SO2I, may vary within a wide range depending on the boiler load and the sulfur content in the coal. Therefore, the control scheme included the following overrides:

- If the outlet SO_2 concentration as measured by the Du Pont analyzer exceeds a set maximum, the limestone feed rate will be stepped up to a preset maximum.
- If the outlet SO_2 concentration drops below a set minimum, the limestone feed rate will be stepped down to a preset minimum.

The first provision minimizes the infringement of the SO_2 emission standard; while the second allows limestone savings by avoiding unnecessary SO_2 removal.

The experience with this first-generation control design at Shawnee, although favorable and limited in time, has revealed several areas for improvement. One specific area that needs improvement relates to the methods of control override mentioned above. These methods of override result in either the overfeeding or underfeeding of limestone with a consequent loss in scrubber performance and sometimes system scaling. The modification proposed would add a proportioning device which would regulate the limestone feed rate, at the overriding conditions, in proportion to the difference between the outlet SO_2 setpoint and the prevailing SO_2 outlet concentration. Additional tests, including some made with the proposed modification, are planned in the future Shawnee test program.

1.6 ONE-SCRUBBER-LOOP FORCED-OXIDATION LIMESTONE TEST RESULTS ON THE TCA WITH AIR EDUCTOR

As an alternative to the types of air sparger used in the venturi/spray tower system, an air eductor was used to accomplish air/slurry contact in the TCA system. Tests were conducted on the one-scrubber-loop TCA system with limestone slurry having high fly ash loadings. No one-scrubber-loop forced-oxidation tests were made with lime slurry because sulfite is the major SO_2 scrubbing species in a lime scrubber. Forced oxidation within the scrubber loop converts the sulfite to sulfate in the slurry liquor, resulting in poor SO_2 removal.

A total of 15 runs were made. These included 11 runs made from June 24 through August 29, 1977, with the air eductor mounted in a vertical position over the oxidation tank, and 4 runs from September 9 through October 4, 1977, with the air eductor in a horizontal position beside the oxidation tank (see Section 12). Major conclusions from these runs were as follows:

- Under the base case conditions of 30,000 acfm gas rate, 1200 gpm TCA slurry rate, 1600 gpm eductor slurry rate, 15 percent recirculated slurry solids with fly ash loading, and 8- to 12-ft slurry level in the effluent hold tank (oxidation tank), sulfite oxidation better than 90 percent was achieved at an eductor inlet pH range of 4.95 to 5.45 and air stoichiometric ratios as low as 2.0 atoms oxygen/mole SO_2 absorbed.
- The dewatering and handling characteristics of slurry solids oxidized to 90 percent or higher in a one-scrubber-loop system were as good as those in a two-scrubber-loop system.
- With a single-tank configuration and limestone addition to the effluent hold tank, low hold tank pH hence, low SO_2 removal was necessary to achieve good sulfite oxidation. The SO_2 removal could be improved, however, by limestone addition to the TCA inlet slurry stream instead of the hold tank.
- Operation in a two-tank configuration allowed for a higher pH to the TCA for good SO_2 removal and a lower pH to the eductor for good sulfite oxidation. Sulfite oxidations of up to 98 percent were achieved with satisfactory SO_2 removal (in the range of 80 to 90 percent).
- SO_2 removal in a one-scrubber-loop forced-oxidation system tended to be a few percentage points higher than the predicted SO_2 removal

under similar operating conditions without forced oxidation. Air stripping of carbon dioxide (CO_2) from the liquor and additional slurry agitation by air, both of which promote the limestone dissolution rate, are believed to cause the SO_2 removal enhancement.

- No significant difference in sulfite oxidation efficiency was observed between operations with the air eductor in the vertical, top-entry position or operations with the air eductor in the horizontal, bottom-entry position.
- Sulfite oxidation was unsatisfactory (about 60 percent) when the eductor slurry flow rate was reduced from 1600 to 1200 gpm. Decreased agitation in the oxidation tank at the lower flow rate, rather than the reduced air stoichiometric ratio, is believed to be the main reason for poor oxidation.
- Air eduction by the eductor was as predicted by the manufacturer. Air flow rate was sensitive to the depth of the eductor's submergence in the slurry, ranging from 600 scfm at zero submergence to 200 scfm at 12-ft submergence, at a 1600 gpm slurry rate. A total of 200 scfm of air was sufficient to achieve good sulfite oxidation at 1600 gpm slurry flow.
- Air/slurry contact was hampered by the configuration of the eductor discharge hold tank (20-ft diameter tank with only 8- to 12-ft normal liquid depth). A smaller diameter but deeper tank would probably have given better oxidation efficiency.
- Erosion of the air eductor with limestone slurry having high fly ash loading (in limestone/fly ash service) was a problem. The eductor body was constructed of neoprene-lined carbon steel. The rubber near the nozzle had eroded in a circular pattern after 1500 operating hours, and the carbon steel body was eroded through after an additional 550 hours. The stellite nozzle and whirler showed only minor erosion.

1.7 LIMESTONE RELIABILITY TEST ON THE TCA WITH HIGH FLY ASH LOADING IN THE FLUE GAS

From October 20 through November 21, 1977, a month-long limestone reliability test was conducted on the TCA system (see Section 13). Flue gas with high fly ash loading (3 to 6 grains/dry scf) was used in the test. The objectives of the test were to meet the current EPA New Source Performance Standard (NSPS) of

1.2 lb SO_2/MM Btu and 0.10 lb particulate matter/MM Btu, while achieving reliable system operation with respect to scaling and plugging.

After two exploratory runs (October 7 to 20, 1977), the following test conditions were selected to meet the objectives of the reliability test:

Gas rate = 20,000 to 30,000 acfm @ 300°F
Slurry rate = 1000 gpm
Recirculated slurry solids concentration = 15%
Total residence time (three series tanks) = 14.4 minutes
Limestone stoichiometry (controlled) = 1.2 mole Ca/mole SO_2 absorbed
Total static bed height (three beds) = 22.5 inches

The gas flow rate was varied according to the No. 10 Boiler load which normally fluctuated between 100 and 155 MW.

Reliable operation of the TCA system was demonstrated during the one-month test, with a scrubber availability of 99.3 percent. Average SO_2 removal for the entire run was 87 percent at 2800 ppm average inlet SO_2 concentration. This corresponds to an average emission of 1.0 lb SO_2/MM Btu, well within the EPA standard of 1.2 lb SO_2/MM Btu. However, due to wide fluctuations in inlet SO_2 concentration and slow system or operating response time, the SO_2 emissions at times exceeded the EPA standard for periods greater than the three hours allowed by existing EPA regulations.

Average particulate loading was 0.043 grain/dry scf corresponding to an average emission of 0.083 lb particulate/MM Btu. Although the EPA standard of 0.10 lb particulate/MM Btu was exceeded in a few measurements; however, on the average, this standard was not exceeded.

1.8 LIMESTONE TEST RESULTS WITH CEILCOTE EGG-CRATE TYPE PLATE PACKING ON THE TCA

An egg-crate type packing support plate manufactured by Ceilcote Company was tested as TCA internals as an alternative to the 1-5/8 inch diameter, 6.5 gram solid nitrile foam spheres. The plate dimensions were 2 ft x 2 ft x 2 inch, with 1-3/16 inch square openings. They were made of fiberglass filled polypropylene. Two one-week tests were conducted from November 24 through December 9, 1977 (see Section 14) to study the performance of the Ceilcote plates with respect to SO_2 removal, particulate removal, and turn-down capability.

Twenty-three layers of Ceilcote plates (46 inches in height) were installed between the second and third bar grids. The number of plate layers was selected to give an estimated pressure drop of about 8 inches H_2O (including the four grids) which is normally obtained with 15 inches total static height of foam spheres (three beds) operating at 30,000 acfm gas rate and 1200 gpm slurry rate.

Under the typical operating conditions at full gas load (30,000 acfm gas rate, 1200 gpm slurry rate, 15 percent slurry solids with high fly ash loading, 12 minutes residence time, and 1.2 moles Ca added/mole SO_2 absorbed), SO_2 removal with 23 layers of Ceilcote plates averaged 76 percent at 3200 ppm average inlet SO_2 concentration. This SO_2 removal was slightly lower than the 80 percent predicted for 15 inches of foam spheres under the same operating conditions.

When the gas rate was turned down to 18,000 acfm (with other test conditions unchanged), the SO_2 removal for the Ceilcote plates was 86 percent at 3050 ppm SO_2, considerably higher than the 78 percent predicted for the foam spheres. Thus, the Ceilcote plates possess better turndown capability than a TCA unit operating with spheres under equivalent conditions.

Particulate removal efficiencies at full gas load for the Ceilcote plates and for the foam spheres were similar (about 98.9 percent). At 18,000 acfm, the removal efficiency for the Ceilcote plates decreased to 98.4 percent, lower than the 99.1 percent experienced in a previous TCA test with 15 inches of spheres and at 20,000 acfm. However, pressure drop across the Ceilcote plates was only 2.9 inches H_2O compared to about 4.5 inches H_2O for the three sphere beds.

No plugging occurred during the two Ceilcote plate test runs. Minor scale formation was observed along the edges of some plates. However, the overall duration of both runs was not sufficient to determine reliability.

In summary, Ceilcote plates give much better SO_2 removal efficiency under turndown conditions compared with sphere beds of similar operating conditions.

1.9 ONE-SCRUBBER-LOOP FORCED-OXIDATION LIMESTONE TEST RESULTS ON THE TCA WITH AIR SPARGER

Because of the erosion problem with an air eductor (see Subsection 1.6), further one-scrubber-loop forced-oxidation testing on the TCA was conducted using an air sparger having 40 1/4-inch diameter holes, similar to the one used in the venturi/spray tower system. As in the testing with the air eductor, only limestone slurry with high fly ash loading was used. Seven runs were made from December 9, 1977 through January 24, 1978, using either one or two tanks. In addition, one run was made from May 31 to June 8, 1978, with limestone slurry and added MgO (see Section 15). Important conclusions from these tests are listed below:

- In similar oxidation tank environments, higher sulfite oxidation efficiency was achieved in the venturi oxidation tank than in the TCA oxidation tank (95 to 100% versus 90 to 95%). The poorer performance on the TCA system was attributed to the weaker agitation in the TCA oxidation tank.
- With two tanks in series, 94 percent sulfite oxidation was achieved at an air stoichiometry of 1.7, oxidation tank pH of 5.45, and an oxidation tank level of 18 ft.
- Higher air stoichiometry (about 1.9) was required to achieve a similar degree of oxidation (94 percent) in a one-tank configuration because of higher pH.
- Operation in the two-tank mode gave better limestone utilization and SO_2 removal than the one-tank mode.
- As expected, MgO addition did not enhance the SO_2 removal when oxidation was forced within the scrubber loop.

Further single-loop forced-oxidation tests on the TCA system will be conducted when a higher speed agitator is installed in the oxidation tank.

1.10 TCA LIMESTONE/MgO AND LIME/MgO TEST RESULTS

From late January 1978 through the end of the report period, the TCA system was operated with lime or limestone slurry with added MgO and without forced oxidation (see Sections 16 and 17). Flue gas with high fly ash loadings was used in all tests. These tests were conducted to try to resolve some of the inconsistent results obtained in a similar test series made earlier in April through November 1976. In those earlier tests, air leakage into the scrubber downcomer was suspected during some of the runs, such air leakage was probably the cause of higher than expected sulfite oxidation and gypsum saturation.

Unfortunately, coals from many different sources were burned in Boiler No. 10

in the first quarter of 1978 during the coal miner's strike, resulting in as much as tenfold variation in inlet SO_2 concentrations (320 to 3400 ppm). The wide fluctuations in the inlet SO_2 concentration not only created process control problems, but also caused difficulties in the data interpretation and in the run-to-run comparison of test results. Therefore, the inconsistent results obtained earlier were never resolved.

1.10.1 Limestone/MgO Tests

The general conclusions that can be drawn from the limestone/MgO tests are listed below:

- Higher effective Mg^{++} concentration is needed in a limestone system than a lime system to achieve a similar degree of SO_2 removal enhancement. This is probably due to the lower pH (5 to 6) inherent in the limestone slurry, where the sulfite-bisulfite equilibrium favors a shift toward nonscrubbing bisulfite species.
- Under typical TCA operating conditions, SO_2 removal improved by about 15 percentage points with 9000 ppm effective Mg^{++} concentration.
- Addition of MgO at the levels tested did not always result in a gypsum-subsaturated mode of operation. Lower sulfite oxidation generally gave lower gypsum saturation.
- No correlation appeared to exist between gypsum saturation and SO_2 make-per-pass. However, gypsum scaling potential tended to be higher (incipient scaling gypsum saturation level tended to be lower) at higher SO_2 make-per-pass.

1.10.2 Lime/MgO Tests

The general conclusions that can be drawn from the lime/MgO tests are listed below:

- At low inlet SO_2 concentrations encountered (1600 to 2000 ppm), sulfite oxidation was 10 to 15 percentage points higher than normal. Higher O_2/SO_2 ratio in the inlet flue gas probably caused the higher oxidation.

- Improvement in SO_2 removal with 2000 ppm effective Mg^{++} concentration was not discernible when the inlet SO_2 concentration was low (1600 to 2000 ppm). In this case, gas-phase mass transfer may become rate-controlling. High sulfite oxidation at the lower inlet SO_2 concentrations would also render Mg^{++} ion ineffective (sulfite concentration in liquor reduced) in SO_2 removal enhancement.

- As in the limestone/MgO tests, lower sulfite oxidation tended to give lower gypsum saturation. No correlation appeared to exist between SO_2 make-per-pass and gypsum saturation. At similar gypsum saturation levels, gypsum scaling potential appeared to be higher at higher SO_2 make-per-pass. (The incipient scaling gypsum saturation level tended to be lower at higher SO_2 make-per-pass).

- Within the range of the hold tank residence times tested (3.0 to 4.1 minutes), lower residence time resulted in lower gypsum saturation under a similar sulfite oxidation level.

1.11 FLUE GAS CHARACTERIZATION TEST RESULTS

The results of flue gas particulate measurements from special test programs and routine sampling tests are presented in Section 18. Summary results from these tests are presented below.

1.11.1 Special Test Program

A special flue gas characterization test program was set up for the TCA from late January through early March 1977. In addition, a special run was conducted in mid-June 1977, completing a similar test series on the venturi/spray tower system which was reported previously (Reference 4).

The effects of major operating variables on the particulate mass removal and particulate size distribution were studied in these special tests.

Variables investigated for both scrubber systems included gas rate, slurry recirculation rate, inlet flue gas fly ash loading (high or low), and MgO addition. In addition, venturi pressure drop, slurry solids concentration, and mist eliminator configuration were studied for the venturi/spray tower, and mist eliminator wash scheme for the TCA.

For the TCA system, the average total outlet mass loading ranged from 0.042 to 0.065 grain/dry scf with high fly ash loading in the inlet gas, and was 0.026 grain/dry scf with low fly ash loading in the inlet gas.

Mass penetration for the TCA with high fly ash loading in the inlet gas ranged from 40 to 90 percent for 0.1 micron aerodynamic particle size, and less than 2 percent for aerodynamic particle sizes greater than 5 microns. With low fly ash loading in the inlet flue gas, the mass penetration was 25 to 70 percent for 0.1-micron particles, and 10 percent for particles greater than 5 microns.

Mass emission from the TCA with high fly ash loading in the inlet flue gas averaged 0.025 grain/dry scf for particles with actual diameters less than 2 microns (except at low gas or low slurry rate, which gave 0.037 grain/dry scf), and averaged 0.028 grain/dry scf for particles with actual diameters greater than 2 microns (except for the base case run with continuous mist eliminator bottom wash at 0.055 grain/dry scf and the MgO addition run at 0.038 grain/dry scf). With low fly ash loading in the inlet gas, the emission averaged 0.003 and 0.025 grain/dry scf for particles with actual diameters less than 2 microns and greater than 2 microns, respectively.

The single special test, conducted on the venturi/spray tower system during the report period, was made with spray tower-alone operation (venturi plug wide open) with flue gas having low fly ash loading. Inlet particulate mass loading averaged about 0.15 grain/dry scf with 85 percent mass removal. The venturi pressure drop of 2.5 inches H_2O (corresponding to the venturi plug wide open) is believed to have contributed significantly to this high removal; however, there is no way to isolate the spray tower from the venturi to verify this assumption.

1.11.2 Routine Mass Loading Test Results

Particulate mass loadings measured routinely at Shawnee during the other venturi/spray tower and TCA test blocks showed results similar to those obtained during the special test program.

In general, outlet mass loading decreased for both scrubber systems with increasing flue gas pressure drop. The venturi/spray tower system generally yielded slightly lower outlet mass loading than the TCA, because a majority of runs were operated with a 9 inches H_2O venturi pressure drop. The TCA outlet mass loading exceeded the EPA standard of 0.10 lb/MM Btu (corresponding to about 0.052 grain/dry scf assuming 30 percent excess air) when flue gas pressure drops were below about 8 inches H_2O.

1.11.3 Air/Slurry Test Results

Tests with air and slurry were conducted during the No. 10 Boiler outage in April and May 1977 to determine the scrubber mass emissions contributed by the slurry entrainment.

However, the dust loadings in the inlet air were significant, and sometimes exceeded the measured outlet mass loading. It could only be concluded that the actual slurry emissions should be less than the measured values. Within the range of operation, measured emissions ranged from 0.001 to 0.003 grain/dry scf for the venturi/spray tower (with 8 percent slurry solids concentration) and 0.001 to 0.005 grain/dry scf for the TCA (with 15 percent slurry solids concentration). These ranges should be the upper limits of the emissions contributed by the slurry.

1.12 LABORATORY LIMESTONE REACTIVITY TEST RESULTS

Laboratory tests of limestone reactivity were conducted at Shawnee to study the effect of limestone source and grind on reactivity. The results of these tests are presented in Section 19. Limestones from 11 different quarries were tested; each stone was ground to two nominal sizes - 75 percent less than 200 mesh and 90 percent less than 325 mesh.

Two methods were used to test the reactivity:

- HCl Method: 5 grams of dried limestone powder were added to an agitated 300 ml solution of HCl at pH 3 and 25°C and the rise of pH with time was recorded.
- SO_2 Method: First 0.2 mole of limestone was dissolved in two liters of distilled water at 50°C until a constant pH was reached. Then a constant stream (0.273 g-mole/hr) of pure SO_2 gas was bubbled through the slurry and the pH drop with time was monitored.

Some conflicting results were obtained when comparing the two methods. The SO_2 method, although somewhat more involved than the HCl method, is believed to be more appropriate for evaluating limestone reactivity because it more closely resembles actual SO_2 wet-scrubbing process.

Due to lack of equipment, no attempt was made to correlate the limestone reactivity values with physical properties (hardness, average pore size, pore size distribution, porosity, etc.).

Tests have been planned for both the IERL-RTP Pilot Plant and the Shawnee Test Facility to study how SO_2 removal, pH, and stoichiometry are related for different limestone type and grind.

1.13 PRESSURE DROP CORRELATIONS FOR SPRAY TOWER AND TCA

Data obtained from the special pressure drop testing on the Shawnee spray tower and TCA are presented in Section 20. Equations that were used to fit the data are presented below.

1.13.1 Spray Tower Pressure Drop Correlation

For flue gas/slurry operation, the following equation was obtained:

$$\Delta P = 0.0062v^{1.17} \exp(0.084L)$$

where:

ΔP = flue gas pressure drop across four spray headers (4 ft vertical distance between headers), in. H_2O

v = superficial gas velocity in the spray tower, ft/sec at 125°F

L = slurry flow rate to four headers, gpm/ft^2 of spray tower cross-sectional area (Shawnee spray tower cross-sectional area = 50 ft^2)

1.13.2 TCA Pressure Drop Correlation

For air/water operation, the fitted equation was:

$$\Delta P = (\Delta P)_{NS} + 0.0363\ v\ H_S^{0.69}\ \exp(0.014\ L)$$

with:

$$(\Delta P)_{NS} = 0.095\ v\ \exp(0.021\ L)$$

where:

ΔP = TCA pressure drop for three beds and four grids, in. H_2O

$(\Delta P)_{NS}$ = TCA pressure drop for four grids (no spheres), in. H_2O

v = superficial air velocity, ft/sec at 90°F

L = water flow rate per unit scrubber cross-sectioanl area, gpm/ft^2 (TCA cross-sectional area is 32 ft^2)

H_S = total static bed height of 1.5-in. diameter 6.5-gram nitrile foam spheres, in.

All measured pressure drops in excess of 8.0 inches H_2O were excluded from the correlation because of incipient flooding. Any case for which the equation predicts a pressure drop greater than 8.0 inches H_2O is likely to be in the flooding region.

1.14 ANALYSIS OF TRACE ELEMENTS

In July 1977, a program was initiated to routinely monitor the concentrations of trace elements (trace metals, nitrogen oxides, total organic carbon) in the slurry liquor, which may catalyze or inhibit the oxidation of sulfite (see Section 21). It is hoped that, through this trace element monitoring program, any unexpected excursions in sulfite oxidation level would be reflected in unusual variations of trace element concentrations from the normal levels. However, no unusual excursion in sulfite oxidation has been encountered since the monitoring program was started.

The trace metals being monitored are Fe, Mn, Mo, Ni, Ti, and V. Nitrite/nitrate and total organic carbon (TOC) are also being analyzed. Typical concentrations of these elements in ppm are:

	Fe	Mn	Mo	Ni	Ti	V	NO_2/NO_3	TOC
Venturi inlet	5	42	5	1	0.4	1	45	5
TCA outlet	7	7	5	0.4	0.3	1.5	15	2

The high value of 42 ppm Mn at the venturi inlet is typical during two-loop forced oxidation and may be the result of more soluble oxidized manganese compounds.

1.15 RESULTS OF WASTE SOLIDS DEWATERING AND CHARACTERIZATION STUDIES

Section 22 presents the results of special waste solids dewatering and characterization studies, such as the evaluation of a Lamella gravity settler thickener, filter leaf tests, hydrometer and pipette particle size distribution tests, evaluation of hydroclones, scanning electron microscope (SEM) analysis, and gypsum crystallization study. Results of routine cylinder settling tests and Buchner funnel filtration tests are also presented.

A brief summary and conclusions of these studies are given below.

1.15.1 Lamella Gravity Settler Thickener Test Results

Testing of a Lamella inclined plate settler thickener, Model LGST No. 3 manufactured by Parkson Corporation, was conducted from July through November 1977. The tests were designed to determine the maximum clarification and thickening capacity of the unit with different slurry types and feed rates. The unit consisted of a rectangular clarification tank containing a series of inclined parallel plates, which was mounted on a circular thickening tank containing a picket fence-type rake. The inclined plate pack had a total settling area of 115 sq.ft. with 57.5 sq.ft. utilized as effective clarification area. The thickener tank was 4 ft in diameter and 10 ft in height. The overall height of the unit was 20 ft.

The following conclusions were drawn as a result of the tests:

- The Lamella settler requires about one-sixth the land area and has a smaller slurry inventory, compared with a conventional clarifier having equivalent settling area.
- Oxidized slurry at 15 weight percent solids has surface loading rates (gallons of slurry per minute per ft^2) 5 to 10 times that of unoxidized slurry.
- Flocculant addition greatly increased the surface loading rate of both oxidized and unoxidized slurry.
- After initial modifications, the Lamella settler operated free from scaling, plugging, and mechanical problems.
- In comparison with conventional settlers, the Lamella settler is superior for clarification but offers little advantage for thickening.

1.15.2 Cylinder Settling and Funnel Filtration Test Results

Cylinder settling and Buchner funnel filtration tests were conducted routinely at Shawnee to monitor and detect any gross changes in the slurry dewatering characteristics. The initial settling rate indicates the rate at which solids fall during the unhindered portion of settling in a clarifier. Ultimate settled solids concentration in the cylinder represents that achievable in a thickener or settling pond. Funnel test cake solids concentration represents that obtainable on a vacuum filter-type dewatering device. The test results are summarized below:

- The average range of the initial settling rate was 0.7 to 1.2 cm/min for an oxidized slurry and 0.2 to 0.4 cm/min for an unoxidized slurry, regardless of high or low fly ash loading.
- The initial settling rate of unoxidized slurry is probably limited by calcium sulfite particles, while fly ash is probably the limiting factor for oxidized slurry.
- The average range of ultimate settled solids and funnel filtration solids was 70 to 76 weight percent for unoxidized slurry.
- In a two-scrubber-loop oxidation with limestone slurry and high fly ash loading, the addition of MgO (8000 ppm effective Mg^{++}) slightly reduced the initial settling rate, ultimate settled solids, and funnel test cake solids.
- For limestone slurry with 5000 ppm effective Mg^{++} and high fly ash loading, oxidation in the bleed stream reduced the initial settling rate to half that of other oxidized slurries. The ultimate settled solids were somewhat lower for the slurries with magnesium, but the funnel test cake solids were not significantly affected.
- The reduced initial settling rate when magnesium is present is probably the result of an increase in liquor viscosity and density due to the increased total dissolved solids.

1.15.3 Filter Leaf Test Results

Tests were conducted with a standard filter leaf having a cloth area of 0.10 ft^2. The objectives of the test were to identify promising filter cloths for future evaluation on the Shawnee rotary drum vacuum filter and to determine the filtration characteristics of sludges generated under different operating conditions.

Twenty-three cloths were evaluated, ranging in air permeability from 0.8 to 100 cfm/ft^2. These included Technical Fabricators TFI9162, Lamport 7512-SHS, and Ametek STE-F9D8-HJO (air permeability range from 7 to 20 cfm/ft^2), which were normally used on the Shawnee vacuum drum filter. Dry cake production rate for these three cloths ranged from 73 to 112 lbs/hr/ft^2 for lime slurry with high fly ash loading and 108 to 134 lbs/hr/ft^2 for limestone slurry with low fly ash loading. Cake solids concentration for the three cloths ranged from 61.8 to 66.9 weight percent and from 44.6 to 45.3 weight percent for the respective slurry types. None of the other cloths tested showed significantly improved dry cake production rate or cake solids concentration. Weight percent solids in the filtrate increased with the air permeability from 0.0 to 0.36 for lime and from 0.0 to 0.09 for limestone, all within the acceptable limit.

Results of tests at the optimum filtration cycle showed that oxidized cake solids were between 70 and 80 weight percent, regardless of alkali type or fly ash content. Unoxidized lime slurry with low fly ash loading had much lower cake solids of about 50 weight percent.

1.15.4 Results of Particle Size Distribution Tests with Hydrometer and Pipette

Use of conventional settling rate data to assess the effects of process variables on the gypsum particle size distribution generated during forced-oxidation testing can result in misleading interpretation because of the presence of other materials, particularly fly ash, in the slurry. Even with low fly ash loading in the flue gas at Shawnee, the product solids contain about one weight percent fly ash. The fly ash normally settles at a much slower rate than the gypsum produced at Shawnee, masking the true settling rate of the latter. At Shawnee, the limit of settling rate appears to be 1.5 to 2.5 cm/min for oxidized slurry. Therefore, once the true settling rate of gypsum exceeds this limit, any further increase in the average size of gypsum particles due to changes in process variables will not be observed.

Two particle size analysis methods, potentially capable of analyzing gypsum particle sizes in the presence of fly ash, have been briefly assessed. The hydrometer method (ASTM D422-63, reapproved 1972, "Standard Method for Particle-Size Analysis of Soils") involves placing an ASTM hydrometer (151H or 152H in ASTM Specification E 100) in a 1 liter graduated cylinder and observing the hydrometer reading with the time of slurry settling. In the pipette method, a 10-ml pipette is used to periodically withdraw slurry samples from the settling cylinder at a constant depth, and the of samples are analyzed for solids composition and weight to calculate the size distribution using Stokes' Law.

On the basis of the test results, the hydrometer test gives a good indication of the overall size distribution but no information on the fly ash/gypsum distribution. The pipette method appears to be the most promising method for segregating the gypsum size distribution from the fly ash.

1.15.5 Hydroclone Test Results

A limited series of tests was conducted in September and November 1977 to determine the suitability of using a hydroclone as a dewatering device for the FGD slurry. Tests with a small Dorr-Oliver Doxie 5 hydroclone were abandoned early in the program because of plugging problems. Tests with a larger porcelain Dorr-Oliver Dorrclone P50A unit (nominal 15 gpm capacity) were more successful.

For the Dorrclone P50A hydroclone, underflow solids concentration was excellent, at about 55 weight percent, when oxidized limestone slurry with high fly ash loading was used. However, the overflow contained unacceptably high solids concentration at 2 to 3 weight percent. Chemical analysis showed that the fines in the overflow were predominantly fly ash, in the range of 60 to 70 weight percent. The feed slurry concentration was 15 weight percent. The pressure drop across the unit ranged from 10 to 29 psi at 11 to 19 gpm feed rates. About 80 percent of the feed flow went to the overflow. Size distribution analysis by hydrometer method showed that, within the range of tests, the pressure drop and feed rate did not appreciably affect the particle size distributions in the overflow and underflow. The underflow size distribution was only slightly higher than the feed. The overflow solids were about 90 percent less than 15 microns.

Based on the limited test results, the hydroclone is judged to be unsuitable as a dewatering device for waste lime/limestone slurry because of high solids content in the overflow. Relatively high energy requirements (high pressure drop) and possible erosion problems would also make it unattractive for this service.

1.15.6 Scanning Electron Microscope (SEM) Analysis of Oxidized Solids

Solids samples from the venturi/spray tower two-scrubber-loop forced-oxidation system were observed under the scanning electron microscope. These samples were taken from a lime test with high fly ash loading. The spray tower solids (10 percent oxidized) were primarily calcium sulfite hemihydrate crystals of a few microns in size in the shape of plates and rosettes. Solids from the venturi loop, system bleed, clarifier underflow, and filter cake (all 95 percent oxidized) were primarily calcium sulfate dihydrate ranging in size from 20 to 100 microns. These solids were chunky and exhibited no appreciable change in size or morphology once the oxidation step was completed.

1.15.7 Gypsum Crystallization Study

Some theoretical studies were conducted on the application of gypsum crystallization technology to the flue gas desulfurization systems. Because of larger interstitial voids, large crystals (i.e., gypsum solids) will filter more easily than small ones. Therefore, it is desirable to increase the gypsum crystal size and reduce the number of crystal nuclei.

There are two ways nuclei can form:

- Primary Nucleation. A spontaneous clustering of solute molecules into larger stable aggregates in a supersaturated solution.
- Secondary Nucleation. The formation of nuclei by crystal-crystal and crystal-solids collisions. This phenomenon becomes increasingly important as both turbulence and slurry solids content increase.

The modeling assumed that the primary nucleation obeys a "power law" model and that the secondary nucleation is a function of slurry solids content.

On the basis of limited data from the venturi/spray tower two-scrubber-loop forced-oxidation, the modeling results suggested the following: when the oxidation tank solids residence time was halved by reducing the slurry solids content from 15 percent to 8 percent, the primary nucleation is predominant in the venturi oxidation tank. The data showed that both the final settled solids content and the initial settling rate decreased when the solids residence time and the slurry solids concentration were halved.

1.16 OPERATING EXPERIENCE

Section 23 presents the operating experience at Shawnee during lime and limestone testing. A brief summary of this experience is given below.

1.16.1 Scrubber Internals

The strong correlation between high alkali utilization and clean mist eliminator operation has been further confirmed during the report period. From June 1977 to the end of the report period in June 1978, the venturi/spray tower mist eliminator was cleaned only once (in December 1977) after 4183 operating hours. Since that time the mist eliminator has operated for 3308 hours without plugging till the end of the report period. The TCA mist eliminator was cleaned in June 1978 at the end of the report period after 7671 operating hours.

The 316L stainless steel TCA support grids have been in slurry service for about 5 years with no evidence of significant erosion.

Six-gram, 1-5/8 inch diameter solid nitrile foam spheres continued to give satisfactory service with no significant failures. Acceptable levels of initial ball shrinkage and wear have been observed. The average rate of decrease in diameter was 0.07 inch per 1000 hours in 7700 hours of service. The continual decrease in diameter required periodical addition of new spheres to maintain the desired static bed height.

The four slurry spray nozzles in the TCA (Spraco No. 1969F, 316L stainless steel) continued to give excellent service at 5 psi pressure drop both in terms of wear and nonclogging characteristics.

Bete No. ST48FCN, stellite-tipped spray nozzles have been used successfully as the spray tower slurry nozzles. New nozzles were installed in December 1976. Visual inspection showed negligible pitting and relatively uniform wear after 2649 hours of service.

Venturi internals continued to erode significantly in several locations, especially the venturi plug guide vanes and the shroud. However, the operability of the venturi has not been seriously affected. In June 1978, a commitment was made to fabricate and install a new venturi plug drive mechanism. The shroud splash guard was rebuilt. A new shaft was fabricated for the plug limit switch mechanism and new guide vanes and blocks were installed. The old shaft had been in service since March 1972.

A trap-out funnel was installed in the spray tower below the bottom spray header for the two-scrubber-loop forced-oxidation testing. Accumulations of solids on the underside (gas side) of the funnel have been a common occurrence. Spray tower operation, however, has not been adversely affected.

1.16.2 Oxidizers

The air sparger in the venturi/spray tower oxidation tank consisted of an octagonal ring about 4 ft in diameter and made of 3 inch diameter 316L stainless steel pipe sections welded together. The first air sparger had 130 1/8-inch diameter holes on the underside. This was later replaced by one with 40 1/4-inch diameter holes. Some erosion and plugging of the air holes were experienced, particularly with the 1/8-inch holes. On October 4, 1977, the 40 1/4-inch hole air sparger ring was removed and replaced with a single 3-inch diameter pipe extending to the center of the tank and discharging air downward through an elbow. No plugging or erosion was observed for the 3-inch air pipe. Humidification of the air was not necessary when the air pipe was used.

During December 1977, the 40 1/4-inch hole sparger previously used in the venturi/spray tower system was installed in the TCA oxidation tank. Because of insufficient air compressor capacity, only a limited number of oxidation tests were conducted on the TCA with this air sparger.

The air eductor used on the TCA system for forced oxidtion was a Model ELL-10 special eductor manufactured by Penberthy-Houdaille Industries. The unit was normally operated at 1600 gpm slurry flow. The materials of construction were stellite for the nozzle and whirler and neoprene-lined carbon steel for the eductor chamber and exit throat. The neoprene lining in the jet throat was observed to be chipped off after only 620 hours of service in limestone/fly ash slurry. After about 1800 hours of operation, bare carbon steel was exposed. Tests were terminated after 2055 hours when an epoxy patch on the bare carbon steel failed and the bare carbon steel body eroded through. The stellite nozzle and whirler showed only minor evidence of erosion.

1.16.3 Reheaters

The fuel-oil-fired reheaters with external combustion chamber were manufactured by Bloom Engineering Co. These reheaters have been in service since March 1974 in the venturi/spray tower and May 1975 in the TCA. Both units have operated reliably with only occasional flameout and equipment problems. During the test period, accumulation of dried slurry solids was common in and around the old Hauck inline reheater shell.

1.16.4 Fans

The reliability of the 316L stainless steel induced-draft fans, manufactured by Zurn Industries, has been fair to good during the current operating period. Maintenance has included occasional steam cleaning and replacement of outboard bearings and pillow blocks five times for the two fans during the last 18 months.

1.16.5 Pumps

The Allen-Sherman-Hoff slurry pumps were neoprene-lined pumps with Nelson liquid drive. The pump packing consisted of graphite impregnated asbestos, the sleeves were chrome-plated steel, and the pump seals were of air-flush type (Centriseal). The pumps provided satisfactory service with a moderate maintenance requirement. The most frequent reason for maintenance was repacking. Generally, wide flow variations called for by the test conditions and operations at low flow rate accelerated the repacking frequency.

The positive-displacement variable-speed Moyno pumps were used for fresh lime and limestone slurry feed. Periodic replacements of the worn-out stator and rotor were required.

1.16.6 Alkali Addition Systems

The lime slaker system has given good reliability over the last 18 months of intermittent operation. Maintenance consisted principally of periodic slaker cleaning and the replacement of the slaker grit screen seven times. The screen slaker motor, drive shaft, and bearings were replaced once in February 1978. The process control elements were cleaned and serviced in March 1978.

The limestone dry-grinding system, installed in 1970, has given acceptable performance with moderate maintenance requirements, considering the age of the system.

1.16.7 Solids Dewatering System

The Ametek 3 ft diameter x 6 ft rotary drum vacuum filter required moderate maintenance, except for the filter cloth. During the 19 month report period, the drum speed control was repaired 3 times, the snap-blowback cake discharge mechanism was repaired twice, and the filter cloth was replaced 15 times. Operating experience indicated a relationship between cloth life and the technique by which new cloth was fitted to the drum. A controlled amount of looseness in the fit between the dividers appeared to be desirable for cake discharge and non-blinding.

The Bird 18 inch x 28 inch solid bowl continuous centrifuge was disassembled and inspected on March 22, 1977, after about 4000 hours of operation since the last service by Bird Machine Co. Major wear sites were found at the two center feed ports at the periphery of the screw conveyor, and at the plows on the solids discharge end. Limited stellite hardface welding was performed onsite at that time. The feed pipe was replaced in March 1978. Another inspection in June 1978, 6460 hours after the previous servicing, revealed serious wear in several places, requiring factory repair. The current plans call for factory repair by Bird Machine Co. using tungsten carbide hardfacing on the conveyor tips instead of the stellite used previously.

1.16.8 Instrument Operating Experience

Service requirements for the Uniloc Model 321 L submersible pH electrode assemblies consisted of periodic cleaning and buffering of the electrodes, generally every 2 or 3 days, to ensure accuracy. The electrodes were placed in 50°C water bath to minimize the effect of thermocycling and thus service requirements when they were not in use.

The Du Pont Model 400 UV split-beam photometers for flue gas SO_2 concentration measurement have been accurate and reasonably trouble-free in the last 18 months of service. Cleaning of the sample cell and sample line was required once every 1 or 2 months, and the particulate filter once every 3 to 4 weeks. Ultraviolet lamp failure occurred infrequently and was caused by uncontrollable momentary power fluctuations due to the switching of station power.

Performance of the Teledyne Model 9500 inlet flue gas oxygen analyzer was unacceptable. Frequent failure of the micro fuel cell was the major problem.

Attempts by Du Pont technicians to convert a Du Pont Model 400 UV photometer for SO_2 to analyze NO_2 were unsuccessful.

Foxboro 2800 series and 1800 series magnetic flow meters operated reliably with acceptable accuracy. Periodic scale cleaning was required to improve accuracy and sensitivity.

Both Dynatrol Model CL-10HY U-tube density meters and Ohmart radioactive density meters provided acceptably accurate and dependable service.

1.16.9 Materials Evaluation

The TCA tower rubber lining was generally in good condition although the surfaces where scale was often removed exhibited scabs from chipping tools. There was no evidence of rubber lining separation from the metal wall.

Schedule 80 PVC 1120 (ASTM D-1785) piping of 6-inch and 8-inch sizes has performed satisfactorily in the TCA main slurry line service.

Blisters were observed in some sections of the rubber-lined pipe during a March 1977 inspection. These blisters have not posed an operating or maintenance problem to date.

A test panel (20 x 15 x 3/8 inch) of carbon steel coated with Fluorelastomer CXL-2000, made by Pullman-Kellogg, failed after about 2000 hours of service in the TCA inlet gas duct where flue gas cooling slurry spray impinged across the panel face.

A section of U-shaped Bondstrand FRP pipe was in excellent condition after about 8800 hours of service in the suction line of the TCA main slurry pump.

The Valtek 6-inch butterfly control valve was judged conditionally acceptable for slurry service. The valve disk does wear and will need replacement.

The Fisher 2-inch butterfly control valve has been in intermittent service since September 1976. The fishtail disk was judged to be in excellent condition. The valve body appeared to be wearing faster than the disk in the throttling service.

The Durco 6-inch butterfly valve, installed in late 1975, was in excellent condition after about 3 years of slurry service. The valve service was primarily in the open position.

Visual inspection of the 8-inch Hayward strainers in the TCA slurry service showed further erosion at the basket support ledge and at the lower half of the strainer outlet during an inspection in November 1977. Similar erosion occurred in the 6-inch size units in the venturi/spray tower.

The Elliott strainers in the venturi/spray tower slurry line did not show further erosion of the strainer body.

Section 2

INTRODUCTION

In June 1968, a program was initiated under the direction of the Environmental Protection Agency (EPA)* to test prototype lime and limestone wet-scrubbing systems for removing SO_2 and particulates from flue gases. A test facility was built which operates with flue gas from coal-fired Boiler No. 10 at the Tennesee Valley Authority (TVA) Shawnee Power Station, Paducah, Kentucky. Bechtel Corporation of San Francisco was the major contractor and test director, and TVA was the constructor and facility operator.

Initially, the test facility consisted of three parallel scrubber systems: a venturi followed by a spray tower, a Turbulent Contact Absorber (TCA), and a Marble-Bed Absorber. Testing of the Marble-Bed Absorber was discontinued in July 1973 because of operational problems. These systems were chosen for their ability to remove both SO_2 and particulates from the burning of medium- to high-sulfur coal. Each system has a capacity of approximately 10 MW equivalent of flue gas (35,000 acfm @ 300°F for the venturi/spray tower and 30,000 acfm @ 300°F for the TCA). The systems operate with flue gas containing 1500 to 4500 ppm of SO_2 obtained either upstream (3 to 6 grains/dry scf of particulates) or downstream (0.04 to 0.20 grain/dry scf of particulates) from Boiler No. 10 particulate removal equipment.

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* The National Air Pollution Control Administration prior to 1970

The original testing program at the facility lasted from March 1972 to October 1974. Results are presented in the Summary of Testing through October 1974 (Reference 1). During the original program, emphasis was placed on demonstrating reliable operation. The most significant reliability problem was associated with scaling and/or plugging of mist elimination surfaces. The TCA mist elimination system consisted of a wash tray in series with a chevron mist eliminator, both with underside washing. Long-term operability of this system was demonstrated in limestone service in an 1835-hour test at a scrubber gas velocity of 8.6 ft/sec.* The venturi/spray tower mist elimination system consisted of a chevron mist eliminator with underside washing. At the end of the original testing program, long-term operability of the venturi/spray tower had not been demonstrated.

In June 1974, the EPA, through its Office of Research and Development and Control Systems Laboratory, initiated a 3-year Advanced Test Program at the Shawnee Facility. Bechtel Corporation continued as the major contractor and test director, and TVA as the constructor and facility operator.

The results of advanced testing from October 1974 through April 1975 at the Shawnee Facility are presented in a First Progress Report (Reference 2). During this period, successful operation of a chevron mist eliminator with intermittent top and bottom wash was demonstrated in the venturi/spray tower system in lime service at a superficial scrubber gas velocity of 8.0 ft/sec. In the TCA in limestone service, plugging of the combined wash tray/mist eliminator system was a continual problem at velocities greater than 8.6 ft/sec. Tests were interrupted in May 1975 for a 6-week scheduled maintenance outage on Boiler No. 10.

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* In this report, all gas velocities and liquid-to-gas ratios are at scrubber operating conditions, i.e., saturated gas at scrubber temperature. The scrubber temperature is approximately 125°F under normal operating conditions. The gas velocities are all superficial velocities.

The results of advanced testing at the Shawnee Facility from June 1975 through mid-February 1976 are presented in a Second Progress Report (Reference 3). During this period, the wash tray/mist eliminator system on the TCA was discontinued in favor of a chevron mist eliminator similar to the one used in the venturi/spray tower. Both systems usually operated at their maximum fan capacity (9.6 ft/sec superficial gas velocity in the spray tower and 12.5 ft/sec in the TCA). Significant results were:

- The discovery that the mist eliminator is more easily kept clean at high alkali utilization
- The demonstration that above 85 percent alkali utilization an intermittent bottom wash will keep the mist eliminator free of soft solids (raw water at 1.5 gpm/ft^2 for 6 minutes every 4 hours)
- The demonstration that below 85 percent alkali utilization a continuous bottom wash will limit soft solids accumulation to less than 10 percent mist eliminator restriction (combined raw water and clarifier return liquor at 0.4 gpm/ft^2)
- The demonstration that intermittent top wash prevents scale formation on top mist eliminator blades (raw water for 4 minutes every 8 hours at 0.5 gpm/ft^2)
- The demonstration on the TCA that three hold tanks in series improves limestone utilization. At 85 percent SO_2 removal, limestone utilization was improved from about 60 percent with a single hold tank to about 75 percent with three tanks in series
- The demonstration in an 1143-hour run that the venturi/spray tower in lime service can operate smoothly with a gas rate following a daily boiler cycle from 40 to 100 percent of full load

The results of advanced testing from mid-February 1976 through November 1976 are presented in a Third Progress Report (Reference 4). During this period, short (6 to 8 hours) factorial tests were run on both scrubber systems using lime slurry, limestone slurry, and limestone slurry with added MgO to enhance SO_2 removal. Both these factorial tests and the longer tests discussed below were fitted to mathematical models for predicting SO_2 removal as a function of major process variables, such as liquid-to-gas ratio, scrubber inlet liquor pH, and effective magnesium ion concentration.

On both systems, longer runs of 4 to 8 days each were made to explore operating variables under several modes of operation. These included runs with lime and limestone alkali, with and without added MgO, using flue gas with and without fly ash.

In addition, a series of venturi/spray tower lime runs of 2 to 6 days each allowed collection of scrubber inlet and outlet data characterizing flue gas mass loading, particle size distribution, and SO_3 concentration.

The Third Progress Report also presented an introductory discussion of lime/limestone wet scrubbing chemistry.

This Report presents the results of testing at the Shawnee Facility from November 1976 through June 1978. Test runs during this period were usually of about 2 to 8 days' duration.

During this period, an emphasis was placed on forced-oxidation testing in which calcium sulfite solids ($CaSO_3 \cdot 1/2H_2O$) are converted to gypsum ($CaSO_4 \cdot 2H_2O$) by contacting the slurry with air. In forced-oxidation testing, 95 mole percent or more of the SO_2 in the waste solids product is in the form of gypsum. These high-gypsum solids, with or without fly ash, have better dewatering and solids handling characteristics than solids containing large amounts of unoxidized calcium sulfite. Forced-oxidation solids from the Shawnee rotary drum vacuum filter typically contain only about 15 percent free moisture, compared with 40 to 50 percent for unoxidized solids. The forced-oxidation solids resemble moist soil having reasonable bearing strength, whereas unoxidized solids are thixotropic. The initial settling rates of forced-oxidation solids are about 10 times higher than those for calcium sulfite solids.

Forced oxidation was accomplished at Shawnee either by air sparging a slurry tank or by pumping slurry through an air eductor. The oxidation configurations tested included staged scrubbers (venturi and spray tower operating with separate effluent hold tanks with oxidation of venturi hold tank slurry), one stage (TCA) oxidation, and bleed stream oxidation. All of these oxidation equipment configurations are discussed in Sections 5, 8, 12, and 15.

The venturi/spray tower was used almost exclusively for forced-oxidation testing during this reporting period. Most venturi/spray tower runs were limestone, lime, or limestone/MgO tests with two-stage forced oxidation by air sparging the venturi effluent hold tank. These runs were made with both low and high fly ash loadings. During May and June 1978, a few additional limestone/MgO tests were performed with bleed stream oxidation by air sparge. In March 1977, three lime bleed stream oxidation tests were performed using an eductor; these latter runs were unsuccessful.

About 25 percent of the TCA operation was devoted to forced-oxidation testing, all with limestone or limestone/MgO. Because EPA pilot studies indicated that calcium sulfite solids are needed for adequate SO_2 removal in a one-stage forced-oxidation system, lime testing with forced oxidation was not performed on the TCA.

Prior to December 1977, oxidation on the TCA system was accomplished by an eductor. Bleed stream eductor oxidation tests performed between March and May 1977 proved unsuccessful. Subsequent eductor oxidation of scrubber hold tank slurry was successful. However, air sparging of hold tank slurry was found to be cheaper, more reliable, and less energy intensive than eductor oxidation. Hence, TCA forced-oxidation tests made after December 1, 1977 were with hold tank sparging.

Testing of the TCA without forced oxidation included the following:

- Runs with limestone, limestone/MgO, lime, and lime/MgO
- Limestone runs with low fly ash loading
- Limestone type and grind tests using coarse limestone from the Longview, Alabama quarry, and coarse and fine limestones from the Fredonia, Kentucky, quarry
- Automatic limestone feed control tests
- Tests with Ceilcote support plate packing instead of spheres
- Flue gas characterization tests with limestone to determine the mass loading, particulate size distribution, and SO_3 concentration for both the scrubber inlet and outlet

During a 10-week Boiler No. 10 outage in April and May 1977, air/slurry tests were performed on both systems to quantify the effect of slurry entrainment on scrubber mass emissions. Three one-month long term tests were made. One of these, Run 717-2A, was on the TCA system with limestone and without forced oxidation. The other two were on the venturi/spray tower with two-stage forced oxidation, Run 819-1A with limestone alkali and Run 863-1A with lime. All three of these tests were at variable gas load and high fly ash loading to simulate commercial operation.

Other special topics covered in this report include:

- Laboratory limestone reactivity tests
- Spray tower flue gas/slurry and TCA air/water pressure drop correlations
- Evaluation of trace elements
- Evaluation of waste solids dewatering characteristics for slurries with and without forced oxidation. This includes laboratory settling and filtration tests, special separation equipment (Lamella inclined plate settler and hydroclone), scanning electron microscope of solids, and a gypsum crystallization study

Section 3

TEST FACILITY

Two parallel scrubbing systems were being operated during the Advanced Test Program. Scrubbers incorporated in these systems were:

- A venturi followed by a spray tower
- A Turbulent Contact Absorber (TCA)

Each system operates independently and is capable of treating approximately 30,000 acfm of flue gas from the coal-fired Boiler No. 10 at TVA's Shawnee Power Station. This gas rate is equivalent to approximately 10 MW of power plant capacity.

Boiler No. 10 normally burns a medium- to high-sulfur bituminous coal which produces SO_2 concentrations of 1500 to 4500 ppm in the flue gas. Ductwork to the scrubbers is tied in both upstream and downstream of the Boiler No. 10 particulate removal equipment allowing scrubber operation on flue gas with high fly ash loadings (3 to 6 grains/dry scf) or low fly ash loadings (0.04 to 0.20 grain/dry scf).

3.1 SCRUBBER SELECTION

The major criterion for scrubber selection was the potential for removing both SO_2 and particulates at high efficiencies (defined for the Shawnee Facility as

SO_2 removal greater than 80 percent and particulate removal greater than 99 percent). Other criteria considered in the selection of the scrubbers were:

- The ability to handle slurries without plugging or excessive scaling
- Reasonable cost and maintenance
- Ease of control
- Reasonable pressure drop

The venturi/spray tower and the TCA were chosen to meet these criteria.

The adjustable-throat venturi scrubber in the venturi/spray tower system was manufactured by Chemical Construction Company (Chemico). The venturi scrubber removes the bulk of the particulates. But because the residence time in a venturi scrubber is low, SO_2 removal with lime/limestone slurry is inadequate. The spray tower that follows the venturi scrubber provides additional capacity for the removal of SO_2.

The TCA was manufactured by Universal Oil Products (UOP). It operates with up to three beds of low-density spheres, nominally 1-1/2 inches in diameter, that are free to move between retaining grids. As the incoming flue gas contacts the slurry in these beds, both SO_2 and particulates are removed.

Figures 3-1 and 3-2 (drawn with major dimensions to scale) show the two scrubber systems and the mist eliminators. The chevron mist eliminator used on the two scrubber systems during this testing period is depicted to scale in Figure 3-3. In two-stage forced-oxidation testing on the venturi/spray tower system, a catch funnel as shown in Figure 3-1 is used to separate the spray tower effluent slurry from the venturi effluent slurry.

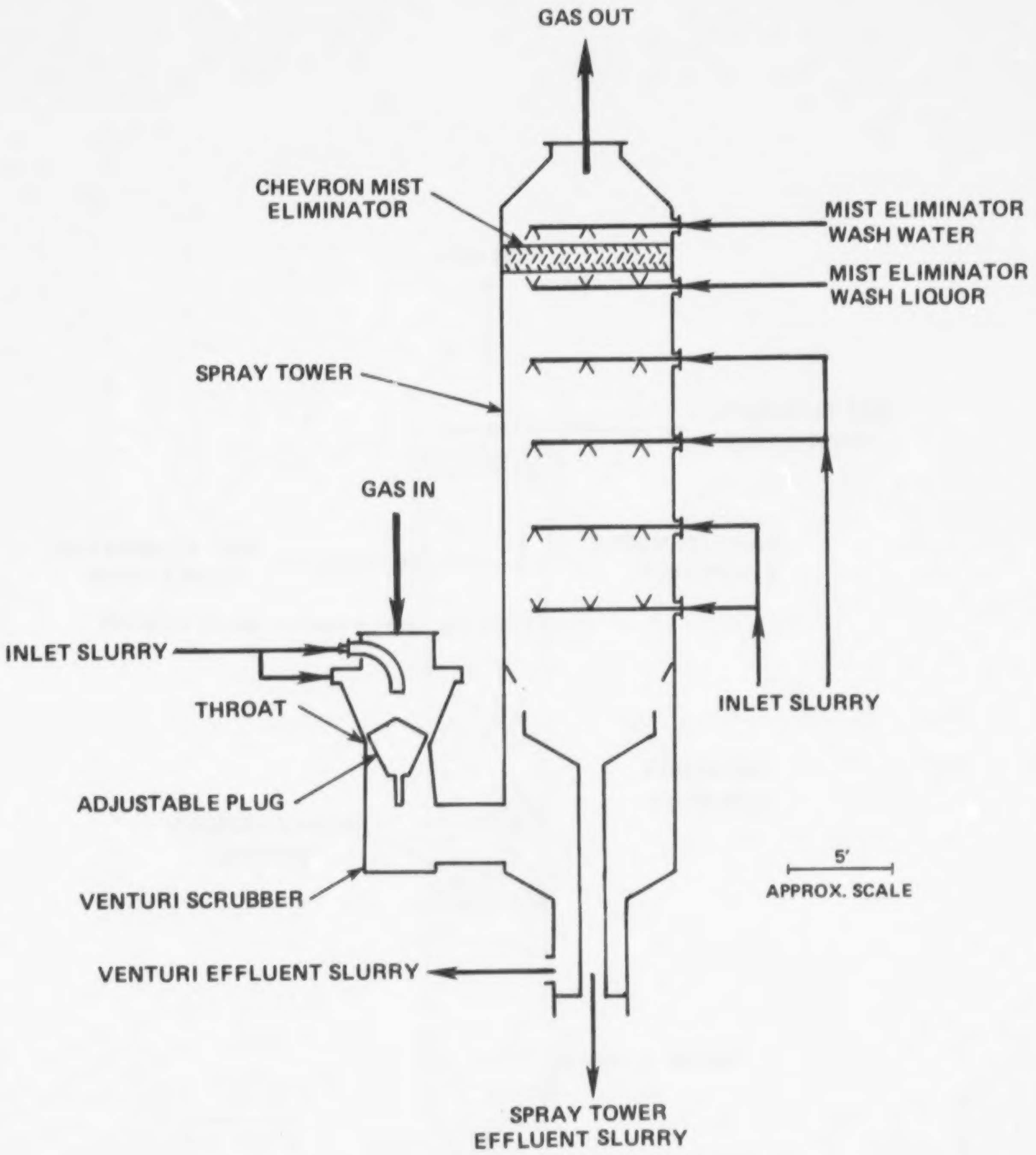
GAS OUT
CHEVRON MIST ELIMINATOR
MIST ELIMINATOR WASH WATER
MIST ELIMINATOR WASH LIQUOR
SPRAY TOWER
GAS IN
INLET SLURRY
THROAT
ADJUSTABLE PLUG
INLET SLURRY
5'
APPROX. SCALE
VENTURI SCRUBBER
VENTURI EFFLUENT SLURRY
SPRAY TOWER EFFLUENT SLURRY

Figure 3-1. Schematic of Venturi Scrubber and Spray Tower

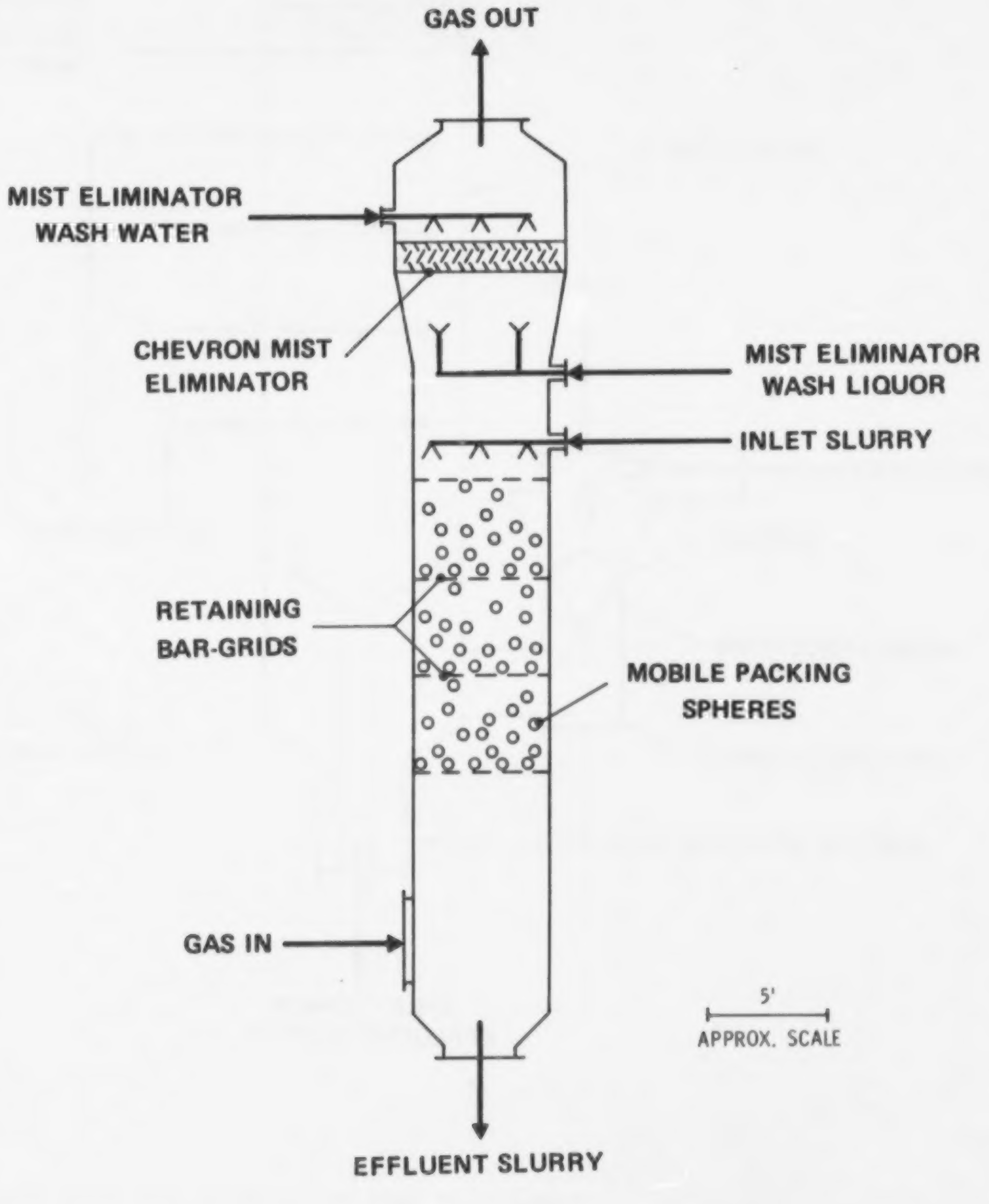
GAS OUT
MIST ELIMINATOR WASH WATER
CHEVRON MIST ELIMINATOR
MIST ELIMINATOR WASH LIQUOR
INLET SLURRY
RETAINING BAR-GRIDS
MOBILE PACKING SPHERES
GAS IN
5'
APPROX. SCALE
EFFLUENT SLURRY

Figure 3-2. Schematic of Three-Bed TCA

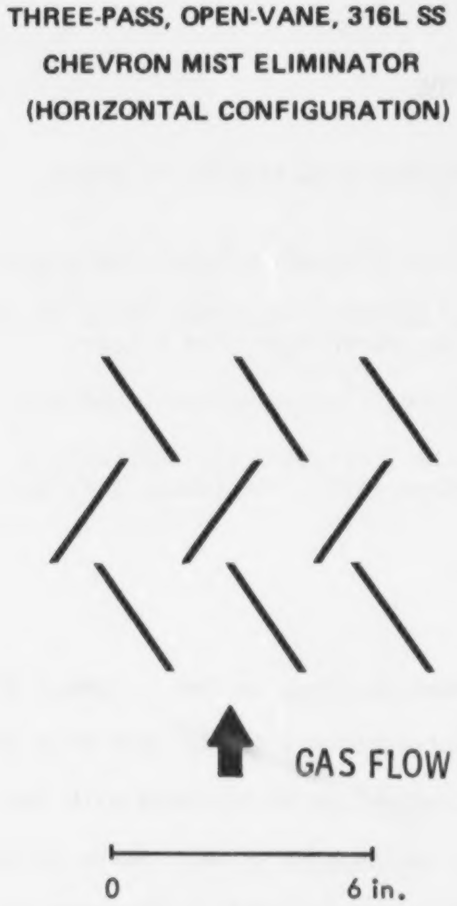
THREE-PASS, OPEN-VANE, 316L SS
CHEVRON MIST ELIMINATOR
(HORIZONTAL CONFIGURATION)
GAS FLOW
0
6 in.

Figure 3-3. Test Facility Mist Eliminator Configuration

The cross-sectional area of the spray tower is 50 ft^2 in both the scrubbing section and the mist eliminator section. The cross-sectional area of the TCA scrubber is 32 ft^2 in the scrubbing section and 49 ft^2 in the mist eliminator section.

3.2 SYSTEM DESCRIPTION

The Shawnee Test Facility contains five major areas:

- The scrubber area (including tanks and pumps)
- The operations building area (including laboratory area, electrical gear, centrifuge, and filter)
- The thickener area (including tanks and pumps)
- The utility area (including air compressors, air dryer, limestone storage silos, mix tanks, gravimetric feeder, and pumps)
- The pond area

The test facility has been designed so that a number of different scrubber internals and piping configurations can be used with each scrubber system. For example, the TCA scrubber can be operated with one, two, or three beds of spheres or with only the support grids. Waste solids separation can be achieved with a clarifier alone or with a clarifier in combination with a filter or a centrifuge. Either system can be operated with a single hold tank or with up to three tanks in series.

The Advanced Program tests have been conducted in closed-liquor-loop operation. A closed liquor loop is achieved when the amount of makeup water input to the system is equal to the amount of water normally leaving the system via the discharge solids and the humidified flue gas. In this report, it is assumed that a closed liquor loop is achieved when the discharge solids concentration is 38 weight percent or higher and no separate liquor is purged. In tests with forced oxidation, solids discharge concentrations of 80 percent and higher were routinely achieved with no separate liquor purge, creating an extremely tight water balance.

Flow diagrams depicting scrubber loop configurations for forced-oxidation testing are presented in subsequent sections of this report. For the venturi/spray tower system, Figure 5-1 shows the two-scrubber-loop configuration, and Figure 8-1 shows the configuration for bleed stream oxidation. For the TCA system, Figures 12-1 and 12-2 show one-tank and two-tank configurations for oxidation by an eductor, and Figures 15-1 and 15-2 show the corresponding configurations for oxidation by sparging.

Figure 3-4 is a flow diagram of the solids dewatering system for either the venturi/spray tower or the TCA. Typically, the venturi/spray tower system has a clarifier followed by a filter, and the TCA has a clarifier followed by a centrifuge.

In May and June 1976, the ductwork to the scrubber systems was modified so that gas can be withdrawn from the boiler either before or after the steam plant particulate removal equipment. In the former configuration, all the entrained particulate matter (fly ash) is introduced into the scrubber; in the latter, the gas to the scrubber contains only a residual amount of fly ash. The gas flow rate to each scrubber is measured by venturi flow meters and controlled by dampers on the induced-draft fans. The concentration of SO_2 in the inlet and outlet gas streams is monitored continuously by Du Pont

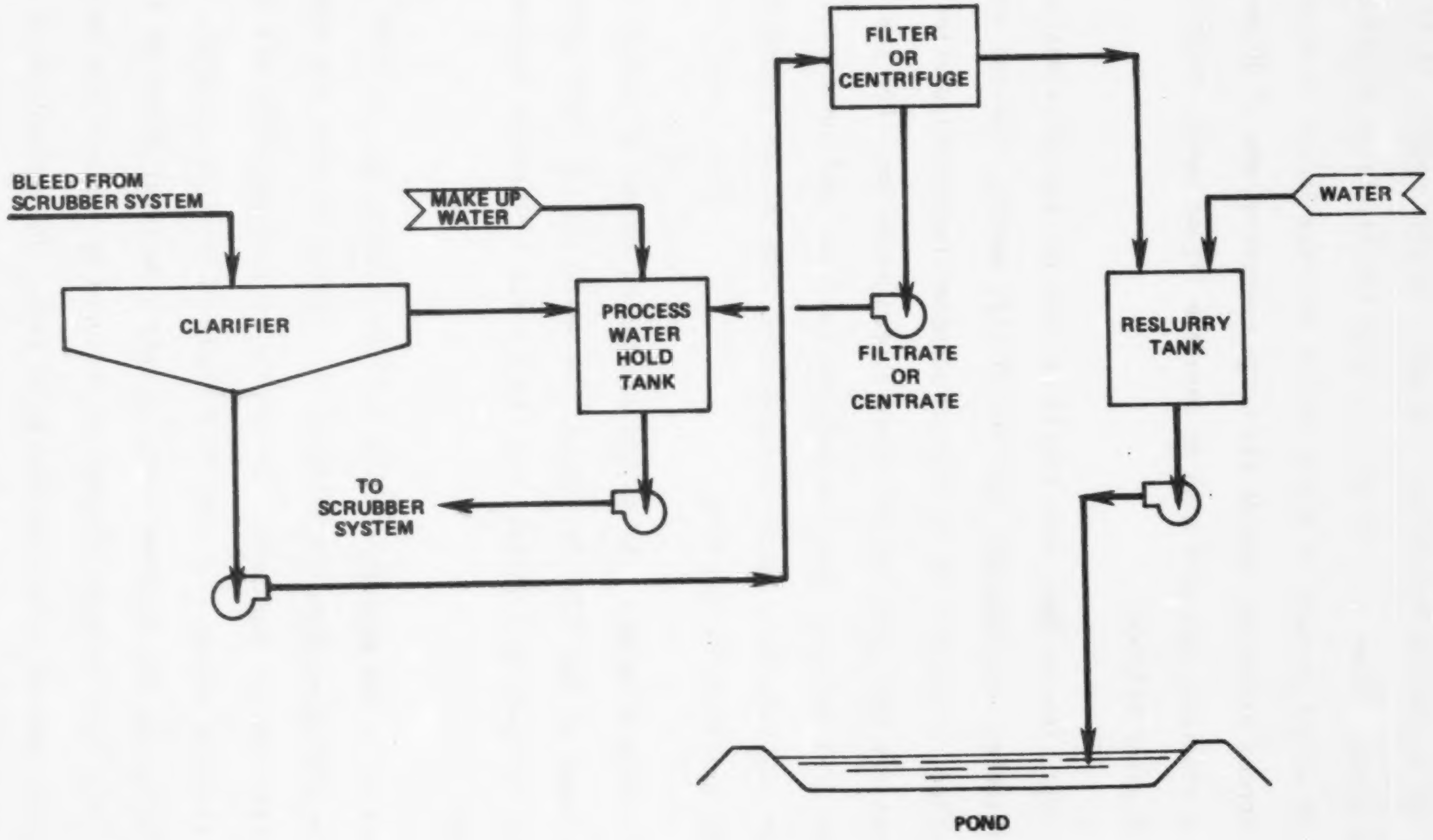
BLEED FROM
SCRUBBER SYSTEM
MAKE UP
WATER
CLARIFIER
PROCESS
WATER
HOLD
TANK
TO
SCRUBBER
SYSTEM
FILTER
OR
CENTRIFUGE
FILTRATE
OR
CENTRATE
WATER
RESLURRY
TANK
POND

Figure 3-4. Flow Diagram for Solids Dewatering System

photometric analyzers.

The scrubbing systems are controlled from a central graphic panelboard, where all significant process variables are on digital display. Important process control variables are continuously recorded. Trend recorders are provided for periodic monitoring of selected data sources. Chemical composition of major streams and scrubber inlet liquor pH are determined several times a day.

3.3 EPA PILOT PLANT

There are two smaller scrubbing systems (300 acfm each) at the EPA Industrial Environmental Research Laboratory in Research Triangle Park, North Carolina. These small pilot-scale scrubber systems are capable of simulating the Shawnee scrubber systems with excellent agreement in the lime/limestone wet-scrubbing chemistry. Preliminary data are generated on the pilot-scale system to determine the validity of new concepts and to guide the selection of those promising concepts that should logically be investigated on the larger scale Shawnee units. Examples of studies originating at the EPA pilot plant and then later investigated at the Shawnee Test Facility include gypsum unsaturated operation, increasing limestone utilization, forced oxidation, and magnesium-enhanced lime and limestone scrubbing.

Section 4

ADVANCED TEST PROGRAM

This section contains a description of the Shawnee Advanced Test Program, which began in June 1974 and extended through June 1978.

4.1 ADVANCED TEST PROGRAM OBJECTIVES AND COMPLETED SCHEDULE

The objectives of the Advanced Test Program are:

- To demonstrate process reliability, with an emphasis on mist elimination systems
- To investigate advanced process and equipment design variations for improving system reliability, economics, and energy requirements
- To evaluate process variations for a substantial increase in alkali utilization for limestone systems
- To evaluate the effect of increased magnesium ion concentration on improving control, reducing gypsum saturation, and increasing SO_2 removal
- To evaluate the efficiency and reliability of lime and limestone scrubbers under conditions of widely varying flue gas flow rate and inlet SO_2 concentration
- To evaluate system performance and reliability without fly ash in the flue gas
- To determine the effectiveness of forced oxidation in producing an improved throwaway sludge product
- To determine the practical upper limits of SO_2 removal efficiency for both limestone and lime scrubbing systems

- To perform reliability demonstration runs on advanced process and equipment design variations
- To characterize stack gas emissions, including inlet and outlet particulate mass loading and size distribution, slurry entrainment, and total sulfate emissions
- To evaluate methods of automatic control
- To provide material for the field evaluation of sludge disposal processes (the field evaluation is being conducted under a separate EPA program)
- To evaluate corrosion and wear of alternative plant equipment components and materials
- To develop a computer program for the design and cost comparison of full-scale lime and limestone systems

A bar chart of the Advanced Test Program, showing the time spent on each of the defined objectives, is presented in Figure 4-1. The period covered by the Fourth Progress Report was from November 1976 through June 1978.

4.2 ANALYTICAL PROGRAM

During the testing, samples of slurry, flue gas, limestone, lime, and coal were taken periodically for chemical analyses, and samples of flue gas were taken for particulate mass loading determinations. A summary of the analytical methods for determining important species in the slurry solids and slurry liquor is presented in Table 4-1. A laboratory procedures manual (Reference 5) was issued in March 1976. A listing of the compositions of the raw material used in the testing program is presented in Appendix C.

Four Du Pont photometric analyzers were used for continuous SO_2 gas analyzing one each at the inlet and outlet of each scrubber. Scrubber inlet liquor pH

Figure 4-1

Schedule for Advanced Test Program

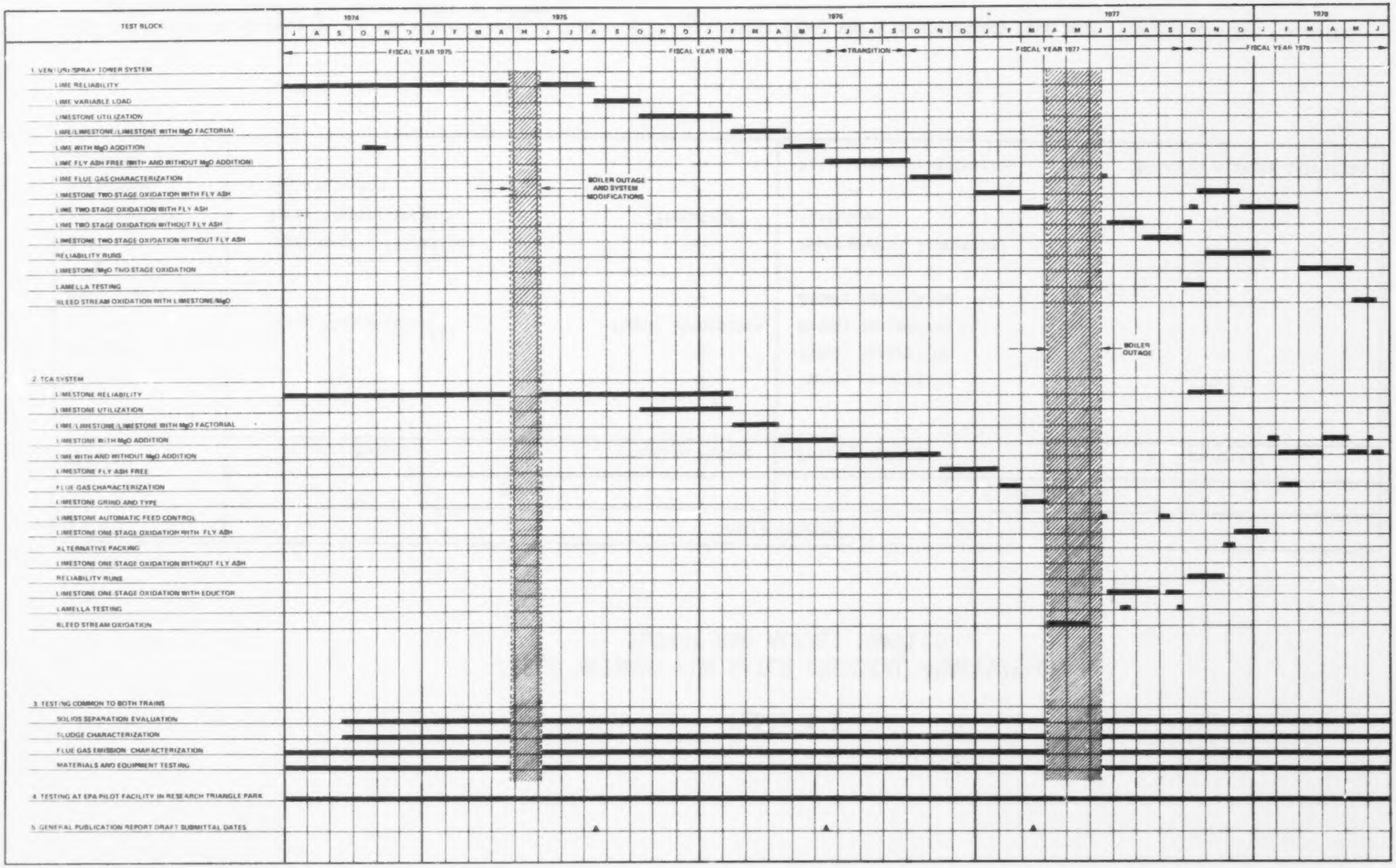

Table 4-1

FIELD METHODS FOR BATCH CHEMICAL ANALYSIS OF SLURRY AND ALKALI SAMPLES

SPECIES	FIELD METHODS			
	SOLIDS		LIQUIDS	
	Primary Method	Backup Method	Primary Method	Backup Method
Sodium	--	--	Atomic absorption	--
Potassium	--	--	Atomic absorption	--
Calcium	X-ray fluorescence(1)	Atomic absorption	Atomic absorption	--
Magnesium	--	--	Atomic absorption	--
Sulfite	Amperometric titration	--	Amperometric titration	--
Total sulfur	X-ray fluorescence(1)	Titration	Titration	--
Carbonate	CO_2 evolution	--	--	--
Chloride	--	--	Potentiometric titration	Mercuric nitrate titration

(1) The X-ray fluorescence method was discontinued in August 1977. Since that time, the primary methods have been atomic absorption for solid calcium, and titration for total sulfur in solids.

was continuously monitored with Universal Interloc pH analyzers. Both scrubber inlet liquor pH and outlet liquor pH are monitored periodically (every 2 hours for inlet, and every 8 hours for outlet) by the laboratory. A modified EPA particulate train (manufactured by Aerotherm/Acurex Corporation) was used to measure mass loading at scrubber inlets and outlets.

4.3 DATA ACQUISITION AND PROCESSING

Data recorded by onsite personnel were sent to the Bechtel home office in San Francisco. Bechtel home office personnel analyzed, summarized and plotted the data on a run-by-run basis.

An onsite analytical data acquisition system, designed and (in part) installed by Radian Corporation, recorded the results of laboratory analyses on printed summary sheets. A minicomputer was used to perform important calculations and print the resultant data.

Onsite, on a daily basis, selected raw analytical and operating data for each 8-hour shift were entered into a National CSS, Inc. (NCSS) computer data file and were verified. San Francisco personnel accessed this data file and loaded it into a NOMAD database on the NCSS system. The database stored the data in a hierarchial order according to scrubber, test run, time, and sample point number. User-written computer programs associated with the database performed further calculations on the raw data, e.g., calculation of percent sulfite oxidation and stoichiometric ratio from solids analytical data. Other user-written programs prepared tables that presented the data for specified times or presented run-averaged data for a specified test sequence. The database run summary tables for November 1976 through June 1978 are presented in Appendix D. Selected hourly test data and scrubber inspection reports were transmitted daily by telecopier from the test facility to San Francisco. Daily data packages, which provided detailed documentation of each day's operation, were mailed to San Francisco.

Section 5

VENTURI/SPRAY TOWER TWO-SCRUBBER-LOOP FORCED-OXIDATION LIMESTONE TEST RESULTS

In lime and limestone wet-scrubbing systems for removing SO_2 and particulate from coal-fired boiler flue gas, disposal of the waste solids product has been a major problem both technically and economically.

The waste solids consist primarily of calcium sulfite hemihydrate, calcium sulfate dihydrate (gypsum), and fly ash. The relative amounts of sulfite and sulfate depend on the degree of oxidation in the scrubber system. In most medium to high-sulfur coal applications, as in the Shawnee Test Facility, natural oxidation of sulfite to sulfate in the scrubber system amounts to only 10 to 30 percent, and calcium sulfite is the predominant material in the waste sludge.

Calcium sulfite wastes present a serious disposal problem because of the difficulty of dewatering. The slurry can be dewatered to only about 50 to 60 percent solids, producing an unstable, thixotropic material unsuitable for landfill. Where space is available, ponding of the untreated sulfite sludge has been practiced. But the pond area may be impossible to reclaim, and in many locations sufficient space is not available.

Beginning in April, 1975, studies conducted by the EPA at the 0.1-MW IERL-RTP pilot plant (Reference 6) have shown that calcium sulfite can be readily oxidized to gypsum by simple air/slurry contact in the hold tank of the scrubber slurry recirculation loop. The oxidized slurry settles by a factor of 10 faster than the unoxidized, sulfite-base slurry, and can be easily dewatered to 80 to 90 percent solids, producing a more tractable material resembling moist soil which may be and suitable for landfill. Furthermore, because of the superior solids dewatering properties, forced oxidation results in a smaller volume of waste solids (even though the molecular weight of gypsum is higher than that of calcium sulfite hemihydrate), and hence lower solids disposal cost.

Preliminary economic evaluations by TVA (Reference 7) have shown that forced oxidation is a more economical method of producing landfill materials than other methods, such as commercial fixation of sulfite sludge with additives and blending sulfite sludge with fly ash.

In the United States, where natural gypsum is widely available, gypsum produced from scrubber systems may be unable to compete extensively with natural gypsum as raw material for the cement and wallboard industries. Thus, the incentive in the United States has been to develop simplified forced-oxidation procedures directed only toward improving waste solids handling and disposal properties. As a disposal material, the gypsum sludge can have high fly ash content; moreover, the oxidation reaction need be carried only to about 95 percent completion.

Based on the findings at the 0.1-MW IERL-RTP pilot plant, a program was initiated in January 1977 at the Shawnee Test Facility to develop procedures for forced oxidation on the larger 10-MW prototype scrubbers. This program has since continued as the major part of the Shawnee Advanced Test Program.

The results of forced-oxidation testing on the venturi/spray tower system are presented in this section and Sections 6 through 8. TCA forced-oxidation test results are given in Sections 12 and 15.

In this section, the results of two-scrubber-loop forced-oxidation limestone tests on the venturi/spray tower system are reported. A total of 15 runs were made (January 4 through March 9 and October 18 through December 15, 1977) with high fly ash loading in the flue gas, including a one-month reliability run (Run 819-1A). In addition, eight runs were conducted (August 12 through October 4 1977), using flue gas with low fly ash loading. Except for the one-month reliability run, each test normally lasted 5 to 6 days, which was judged to be sufficient time to reach kinetic equilibrium and to allow collection of adequate run data.

Major test conditions and important test results for these runs are summarized in Table 5-1. A log of the scrubber operating periods is given in Appendix B. Properties of coal and limestone used during these tests can be found in Appendix C. Appendix D presents computer data base run summaries. Detailed operating conditions and results are summarized in Appendix E. Selected operating data are graphically presented in Appendix F. Average scrubber liquor compositions and the corresponding calculated percent gypsum saturations are given in Appendix G.

5.1 SYSTEM DESCRIPTION

During the month of December 1976, the venturi/spray tower system was modified to allow operation in a two-scrubber-loop configuration with forced oxidation of calcium sulfite to calcium sulfate (gypsum) in the hold tank of the first

Table 5-1

RESULTS OF FORCED-OXIDATION TESTS WITH TWO SCRUBBER LOOPS ON THE VENTURI/SPRAY TOWER SYSTEM USING LIMESTONE SLURRY

Major Test Conditions	801-1A	802-1A	803-1A	804-1A	805-1A	806-1A	806-1B	806-1C	806-1D
Fly ash loading	High	High	High	High	High	High	High	High	High
Gas rate, acfm @ 300^{0}F	25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000
Venturi liquor rate, gpm	400	400	600	600	600	600	600	600	600
Spray tower liquor rate, gpm	1300	1400	1400	1400	1400	1400	1400	1400	1400
Venturi percent solids recirculated (controlled)	15	15	15	15	15	15	15	15	15
Residence times, min: Oxidation tank(2)	17	17	11.3	11.3	11.3	11.3	11.3	11.3	11.3
Desupersaturation tank	7	7	4.7	4.7	4.7	4.7	4.7	4.7	4.7
Spray tower EHT	19.4	18	18	18	18	18	18	18	18
Venturi inlet (oxidation tank) pH (controlled)	4.5	5.0	5.0(3)	5.0	5.0	4.5	4.5	4.5	4.5
Venturi pressure drop, in. H_2O	9	9	9	9	9	9	9	9	9
Air rate to oxidation tank, scfm	400(4)	400(4)	400(4)	400(4)	400(4)	250(4)	150(4)	100(4)	50(4)
Clarified liquor returned to(7)	S.T	S.T	S.T	V. & S.T.	V.	V.	V.	V.	V.
Selected Results									
Percent SO_2 removal	62	60	67	71	78	73	74	73	80
Inlet SO_2 concentration, ppm	3400	3500	3150	3150	3450	3400	2850	3250	3100
Spray tower percent solids recirculated	5.8	6.1	5.4	7.4(8)	15.6	15.1	14.5	14.2	15.9
Spray tower inlet pH	5.7	5.5	5.65	5.8	6.15	6.15	6.1	6.0	6.15
Spray tower limestone stoichiometric ratio	1.20	1.37	1.47	1.45	1.53	1.30	1.25	1.25	1.35
Spray tower inlet liquor gypsum saturation, %	75	110	120	105	25	20	55	50	15
Spray tower sulfite oxidation, %	13	16	16	15	11	10	15	17	15
Overall sulfite oxidation, %	93	95	96	97	98	99	98	97	67
Overall limestone utilization, %	91	83	87	88	87	95	95	96	91
Venturi inlet liquor gypsum saturation, %	100	110	105	105	95	95	95	100	105
Venturi inlet liquor sulfite concentration, ppm	29	24	21	22	16	16	15	15	130
Air stoichiometry, atoms O/mole SO_2 absorbed	4.7	4.7	4.7	4.4	3.7	2.5	1.7	1.0	0.50
Filter cake solids, wt%(10)	81	86	81	85	81	84	82	79	79(11)
Onstream hours	263	256	138	151	112	45	45	54	41

Note: Footnotes for this table are listed at the end of Table 5-1 (continued).

Table 5-1 (continued)

RESULTS OF FORCED-OXIDATION TESTS WITH TWO SCRUBBER LOOPS ON THE VENTURI/SPRAY TOWER SYSTEM USING LIMESTONE SLURRY

Major Test Conditions	807-1A	808-1A	809-1A	810-1A	811-1A	812-1A	813 1A
Fly ash loading	High	High	Low	Low	Low	Low	Low
Gas rate, acfm @ 300°F	25,0-0	25,000	25,000	25,000	25,000	25,000	25,000
Venturi liquor rate, gpm	600	600	600	600	600	600	600
Spray tower liquor rate, gpm	1400	1400	1400	1400	1400	1400	1400
Venturi percent solids recirculated (controlled)	15	15	15	15	15	15	15
Residence times, min: Oxidation tank(2)	11.3	11.3	11.3	11.3	11.3	11.3	11.3
Desupersaturation tank	4.7	4.7	4.7	4.7	4.7	0	0
Spray tower EHT	18	18	13.4	13.4	13.4	13.4	13.4
Venturi inlet (oxidation tank) pH (controlled)	4.5	4.5	4.5	5.0	5.5	5.5	5.5
Venturi pressure drop, in. H_2O	9	9	9	9	9	9	9
Air rate to oxidation tank, scfm	0	150(4)	150(5)	150(5)	150(5)	150(5)	150(5)
Clarified liquor returned to(7)	V.	V.	S.T	S.T	S.T	S.T	S.T
Selected Results							
Percent SO_2 removal	79	76	82	83	85	93	
Inlet SO_2 concentration, ppm	3350	2850	2450	2700	2600	2350	
Spray tower percent solids recirculated	16.6	15.5	7.9	8.1	8.0	7.0	
Spray tower inlet pH	6.25	6.25	5.7	5.8	5.9	5.95	
Spray tower limestone stoichiometric ratio	1.34	1.20	1.30	1.35	1.40	1.93	
Spray tower inlet liquor gypsum saturation, %	8	23	105	105	105	100	
Spray tower sulfite oxidation, %	7	16	21	22	25	25	-(14)
Overall sulfite oxidation, %	18	97	98	98	97	98	
Overall limestone utilization, %	91	98	98	96	96	81	
Venturi inlet liquor gypsum saturation, %	135	100	95	95	105	105	
Venturi inlet liquor sulfite concentration, ppm	555	19	35	25	45	60	
Air stoichiometry, atoms O/mole SO_2 absorbed	0	1.7	1.85	1.65	1.65	1.70	
Filter cake solids, wt%(10)	74(11)	82(11)	80(12)	-(13)	-(13)	86	
Onstream hours	66	65	137	162	184	141	7

Table 5-1 (continued)

RESULTS OF FÓRCED-OXIDATION TESTS WITH TOW SCRUBBER LOOPS ON THE VENTURI/SPRAY TOWER SYSTEM USING LIMESTONE SLURRY

Major Test Conditions	814-1A	815-1A	816-1A	817-1A	818-1A	819-1A	819-1B
Fly ash loading	Low	Low	Low	High	High	High	High
Gas rate, acfm @ 300°F	25,000	35,000	35,000	35,000	35,000	-$^{(1)}$	-$^{(1)}$
Venturi liquor rate, gpm	600	600	600	600	600	600	600
Spray tower liquor rate, gpm	1400	1400	1400	1400	1600	1600	1600
Venturi percent solids recirculated (controlled)	15	15	15	15	15	15	15
Residence times, min: Oxidation tank$^{(2)}$	8.8	8.8	11.3	11.3	11.3	11.3	11.3
Desupersaturation tank	4.7	4.7	4.7	4.7	4.7	4.7	4.7
Spray tower EHT	13.4	13.4	13.4	16.8	14.7	14.7	14.7
Venturi inlet (oxidation tank) pH (controlled)	5.5	5.5	5.5	5.5	5.5	5.5	-$^{(9)}$
Venturi pressure drop, in. H_2O	9	9	9	9	7.5-9	≤9	≤9
Air rate to oxidation tank, scfm	150$^{(5)}$	210$^{(5)}$	210$^{(5)}$	210$^{(6)}$	210$^{(6)}$	210$^{(6)}$	210$^{(6)}$
Clarified liquor returned to$^{(7)}$	S.T	S.T	ST.	V.	V.	V.	V.
Selected Results							
Percent SO_2 removal	91	86	86	83	86	86	85
Inlet SO_2 concentration, ppm	2450	2500	2350	2500	2550	2950	3000
Spray tower percent solids recirculated	8.4	8.4	7.7	8.9	9.6	10	9.6
Spray tower inlet pH	5.95	5.85	5.75	5.9	5.9	5.85	5.9
Spray tower limestone stoichiometric ratio	1.78	1.98	1.68	1.60	1.64	1.65	1.65
Spray tower inlet liquor gypsum saturation, %	100	105	105	100	100	100	110
Spray tower sulfite oxidation, %	27	26	27	21	19	21	19
Overall sulfite oxidation, %	98	96	98	97	98	98	98
Overall limestone utilization, %	83	67	83	82	81	81	83
Venturi inlet liquor gypsum saturation, %	105	105	100	105	105	100	105
Venturi inlet liquor sulfite concentration, ppm	25	40	25	25	25	25	25
Air stoichiometry, atoms O/mole SO_2 absorbed	1.65	1.70	1.80	1.75	1.70	1.45-2.80	1.45-2.80
Filter cake solids, wt%$^{(10)}$	88	87	86	86	86	87	86
Onstream hours	136	306	142	188	141	840	126

Notes:

(1) Gas rate was varied from 18,000 to 35,000 acfm to follow the boiler load.
(2) Oxidation tank level was 18 ft for all runs except Runs 814-1A and 815-1A which were at 14 ft.
(3) Actual venturi inlet pH averaged 4.8.
(4) Used a sparger ring located 6 inches from tank bottom. The sparger ring had 130 1/8-inch holes on the bottom side.
(5) Used a sparger ring located 6 inches from tank bottom. The sparger ring had 40 1/4-inch holes on the bottom side.
(6) Air discharged downward through a 3-inch diameter pipe with an open elbow at center of oxidation tank about 3 inches from tank bottom.
(7) Spray tower loop (effluent hold tank) or venturi loop (oxidation tank).
(8) Controlled by proper flow split of clarified liquor returned to venturi and spray tower loops.
(9) Spray tower limestone stoichiometry controlled at 1.6.
(10) Clarifier and filter in series were used for solids dewatering in all runs except as noted.
(11) Values may not be representative due to changes in oxidation in short runs.
(12) Excludes last half of run when filter was out of service.
(13) Clarifier only was used.
(14) Test with oxidation tank agitator turned off. Terminated after 7 hours because the air sparging alone did not keep the solids suspended.

scrubber (venturi) slurry loop. The first scrubber (venturi) loop was operated at a relatively low pH (4.5 optimum) to provide favorable conditions for oxidation while the second scrubber (spray tower) loop was operated at a higher pH (5.9) for good SO_2 removal.

A typical flow diagram of this set-up is shown in Figure 5-1. To separate the venturi and spray tower scrubber loops, a catch funnel was installed beneath the bottom spray header of the spray tower. To eliminate slurry entrainment through the catch funnel, the bottom spray header had to be turned upward.

The hold tank in the first scrubber stage (venturi) recirculation loop was used as the oxidation tank. This tank was 8 ft in diameter and could be operated at either a 10-, 14-, or 18-ft slurry level. It contained an air sparger ring arranged as shown in Figure 5-2. The sparger ring was made of straight 3-inch 316L SS pipe pieces welded into an octagon of approximately 4 ft in diameter, and located 6 inches from the bottom of the tank. The initial sparger ring had 130 1/8-inch diameter holes pointed downward. This sparger was later replaced with another one that contained 40 1/4-inch diameter holes. The sparger ring was fed with compressed air to which sufficient water was added to assure humidification. The air had to be humidified to prevent local supersaturation and scaling at the sparger holes. In more recent tests, the sparger ring was replaced by a 3-inch diameter pipe with an open elbow discharging air downward at the center of the tank about 3 inches from the tank bottom (not shown in Figure 5-2). Humidification of air was found to be unnecessary when the 3-inch diameter pipe was used.

The oxidation tank had an agitator with two axial flow turbines, both pumping

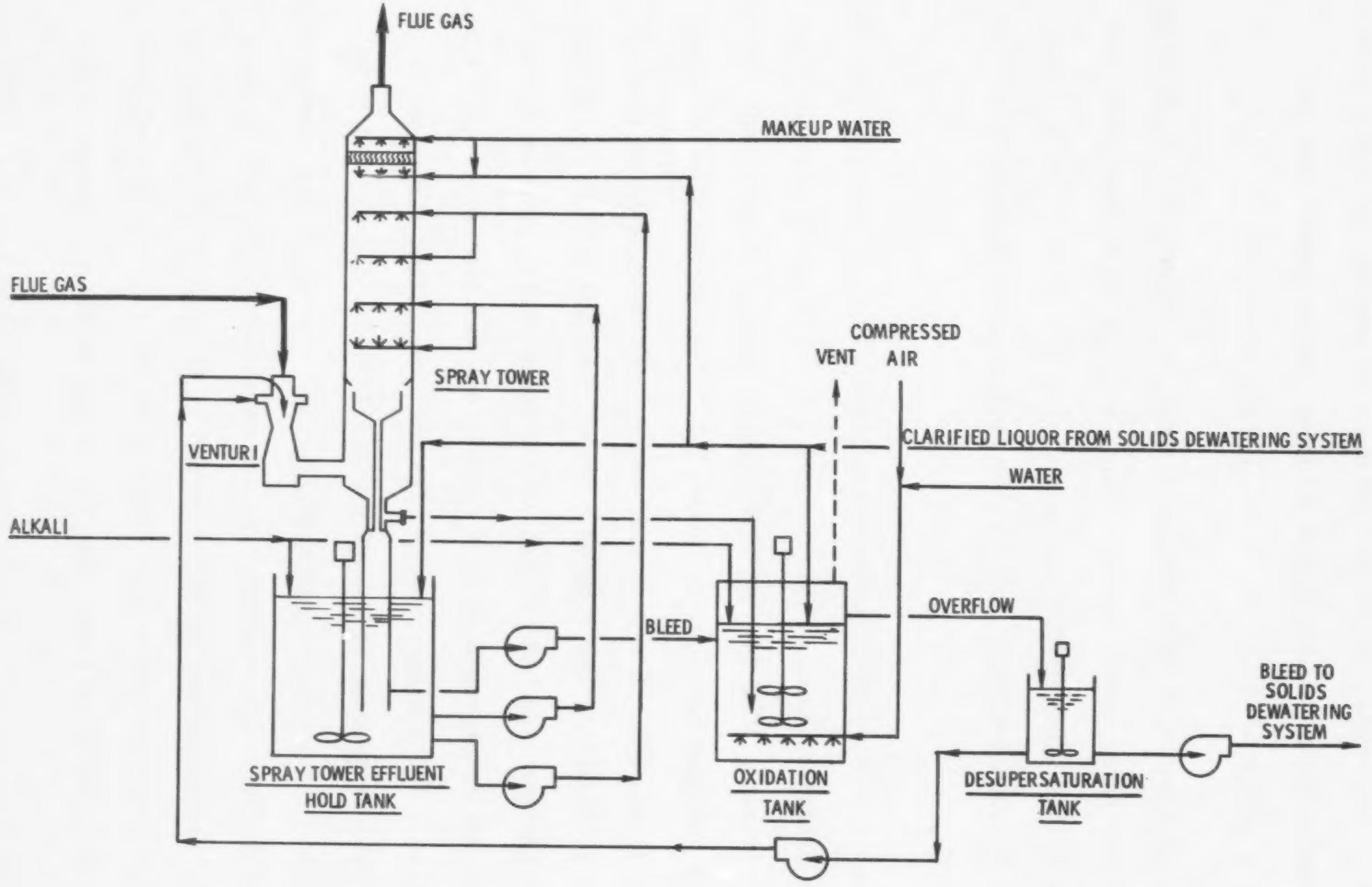
FLUE GAS
MAKEUP WATER
FLUE GAS
COMPRESSED
VENT
AIR
SPRAY TOWER
VENTURI
CLARIFIED LIQUOR FROM SOLIDS DEWATERING SYSTEM
WATER
ALKALI
OVERFLOW
BLEED
BLEED TO SOLIDS DEWATERING SYSTEM
SPRAY TOWER EFFLUENT HOLD TANK
OXIDATION TANK
DESUPERSATURATION TANK

Figure 5-1. Flow Diagram for Two-Scrubber-Loop Forced-Oxidation Tests on the Venturi/Spray Tower System

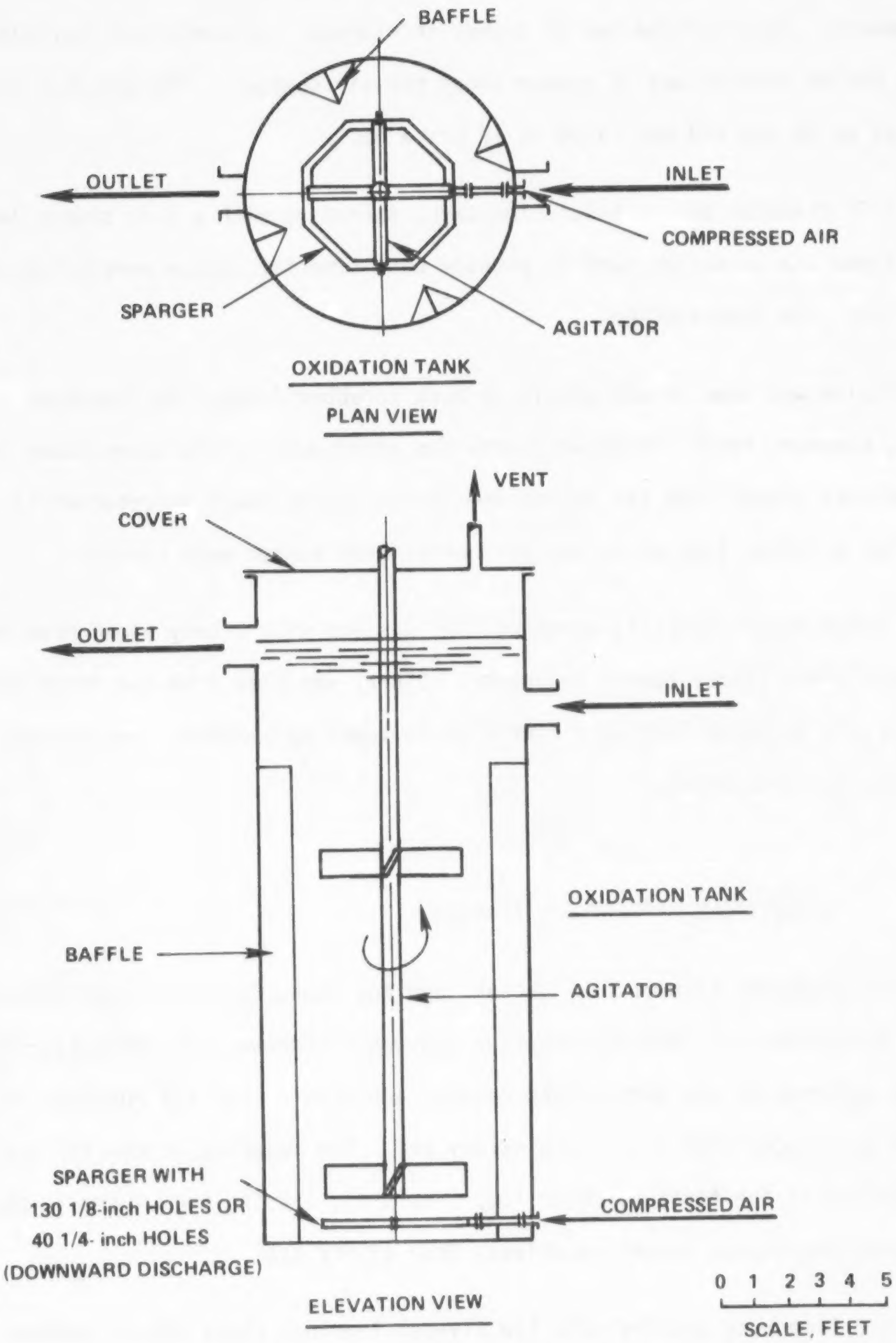
BAFFLE
OUTLET
INLET
COMPRESSED AIR
SPARGER
AGITATOR
OXIDATION TANK
PLAN VIEW
VENT
COVER
OUTLET
INLET
OXIDATION TANK
BAFFLE
AGITATOR
SPARGER WITH
130 1/8-inch HOLES OR
40 1/4- inch HOLES
(DOWNWARD DISCHARGE)
COMPRESSED AIR
0 1 2 3 4 5
SCALE, FEET
ELEVATION VIEW

Figure 5-2. Arrangement of the Venturi/Spray Tower Oxidation Tank with Sparger

downward. Each turbine was 52 inches in diameter and contained four blades. The bottom turbine was 10 inches above the air sparger. The agitator rotated at 56 rpm and was rated at 17 brake Hp.

A 10-ft diameter desupersaturation tank, operating with a 5-ft slurry level, followed the oxidation tank to provide both time for gypsum precipitation and air-free pump suction.

Provision was made to add alkali to both scrubber loops. In limestone testing, however, fresh limestone slurry was added only to the spray tower loop. Clarified liquor from the solids dewatering system could be returned to either scrubber loop or to the mist eliminator bottom wash circuit.

The first stage (venturi) scrubber loop was fed with slurry bleed from the second stage (spray tower) downcomer. Slurry was bled from the first stage (venturi) scrubber loop to a clarifier followed by a rotary drum vacuum filter for dewatering.

5.2 DISCUSSIONS OF TEST RUN RESULTS

In the limestone tests with high ash loadings (Runs 801-1A through 808-1A, and 817-1A through 819-1B), the flue gas was withdrawn from the Boiler No. 10 duct upstream of the particulate removal equipment. Fly ash loadings in the flue gas ranged from 3 to 6 grains/dry scf. The majority of the fly ash was collected in the first scrubber loop (venturi), leaving the slurry in the second loop (spray tower) relatively free of fly ash.

For the limestone testing with low fly ash loadings (Runs 809-1A through 816-1A), the flue gas was taken from the Boiler No. 10 duct downstream of the particulate removal equipment. This flue gas contained particulate concentrations of 0.04 to 0.20 grain/dry scf.

Generally, the results with high and low fly ash loadings are similar, with good sulfite oxidation and good filter cake being achieved in both cases. Table 5-1 summarizes the results of two-scrubber-loop forced-oxidation limestone tests with high and low fly ash loadings.

5.2.1 Startup Test Run 801-1A

In the initial test with high fly ash loading, Run 801-1A achieved 93 percent average sulfite oxidation by simple air sparging in the venturi stage hold tank. Test conditions for Run 801-1A were chosen to approximate those used in the tests at the IERL-RTP pilot plant (Reference 6) and to provide the best oxidation tank environment for oxidation to occur. These conditions included 4.5 pH for optimum reaction rate in the oxidation tank, 18-foot maximum slurry level in the oxidation tank, and an air stoichiometric ratio of 4.7 atoms oxygen/mole SO_2 absorbed, which corresponded to the maximum air compressor capacity of 400 scfm.

The filter cake solids concentration averaged 81 percent which was, the highest ever recorded at Shawnee at the time. In the subsequent runs, when sulfite oxidation was above about 90 percent, filter cake solids concentrations higher than 80 percent were consistently achieved.

Although good oxidation was achieved for this run, the SO_2 removal was poor and averaged only 62 percent at 3400 ppm average inlet SO_2 concentration.

5.2.2 Modifications of Initial Test Conditions to Improve SO_2 Removal

In Runs 802-1A through 805-1A, operating conditions were changed to improve SO_2 removal.

Increasing spray tower liquor rate from 1300 to 1400 gpm and oxidation tank pH from 4.5 to 5.0 (by higher limestone addition rate to the spray tower hold tank) during Run 802-1A gave essentially no improvement in SO_2 removal. Marginal increase in SO_2 removal from 60 to 67 percent was achieved when the venturi liquor rate was increased from 400 to 600 gpm in Run 803-1A.

In Runs 804-1A and 805-1A, the solids concentration in the spray tower recirculation loop was increased by returning the clarified liquor from the dewatering system to the venturi loop rather than the spray tower loop. This change increased the solids in the spray tower loop from 5.4 percent to 15.6 percent, with solids controlled at 15 percent in the venturi loop. The higher solids concentration provided more limestone surface to dissolve in the spray tower loop and the spray tower inlet liquor pH increased from 5.65 to 6.15 (pH controlled at 5.0 in the venturi loop). Overall SO_2 removal increased from 67 percent to 78 percent. Subsequent runs were made with clarified liquor return to the venturi loop.

5.2.3 Optimization of Air Stoichiometric Ratio

Runs 801-1A through 805-1A were made at an air flow rate to the sparger in the oxidation tank of 400 scfm (maximum air compressor capacity) corresponding to an air stoichiometric ratio of about 4.5 atoms oxygen per mole of SO_2 absorbed. Runs 806-1A and 807-1A were made to determine the minimum air rate required for nearly complete sulfite oxidation. The following tests were made at 4.5 oxidation tank pH and 18-foot tank level, using the 130-hole air sparger:

Effect of Air Stoichiometry on Sulfite Oxidation for Limestone Slurry (4.5 pH) with High Fly Ash Loading

Run	Air Rate, scfm	Air Stoichiometry, atoms oxygen/mole SO_2 abs.	Percent Sulfite Oxidation
806-1A	250	2.5	99
806-1B	150	1.7	98
806-1C	100	1.0	97
806-1D	50	0.5	67
807-1A	0	0	18

The break in oxidation appeared to occur somewhere between 1.0 and 0.5 air stoichiometry. This compares with an air stoichiometry of about 2.6 required in tests at the IERL-RTP pilot plant run under similar conditions without fly ash (Reference 6). It has been postulated that either an oxidation catalyst such as manganese, possibly introduced with the fly ash, or better mass transfer due to mechanical agitation, accounts for the excellent oxidation. Although such a catalyst is suspected, one has not yet been identified in the Shawnee system.

Based on these tests, an air rate of 150 scfm, corresponding to an air stoichiometry of 1.7 atoms oxygen per mole SO_2 absorbed, was chosen as a standard rate for subsequent runs made at 25,000 acfm gas rate. Run 808-1A was made at this air rate to confirm the good oxidation (97 percent).

5.2.4 Limestone Tests with Low Fly Ash Loading

Following a series of tests with lime slurry (see Section 7), testing with limestone was resumed but with low fly ash loading in the flue gas (Runs 809-1A through 816-1A).

In general, the results with high and low fly ash loadings were similar. High sulfite oxidation and filter cake solids content were achieved in both cases. The majority of fly ash was removed by the venturi and ended up in the first (oxidation) slurry loop. It is postulated that, even with low fly ash loading in the flue gas, the oxidation catalysts introduced with fly ash may still be present in sufficient quantity for good oxidation.

During the testing with low fly ash loading, the spray tower slurry solids concentrations were sufficiently high (about 8 percent) for good SO_2 removal, even though all the clarified liquor was returned to the spray tower loop. (The venturi slurry solids concentration was controlled at 15 percent as in the case of high fly ash loading.) This allowed the continuous washing of the bottom side of the mist eliminator with a diluted clarified liquor, which permitted operation of the spray tower at higher limestone stoichiometries without mist eliminator fouling.

5.2.5 Effect of Oxidation Tank pH

Runs 809-1A through 811-1A were made to determine if the slurry liquor pH in the oxidation tank affected the degree of sulfite oxidation. Over a pH range of 4.5 to 5.5 no adverse effect was seen. Sulfite oxidation remained 97 percent. Higher pH levels, where a drop in oxidation might be expected, were not investigated as they would be outside of the practical operating range for a two-scrubber-loop limestone system. The increase in pH also resulted in increased SO_2 removal up to 85 percent in Run 811-1A.

5.2.6 Effect of Desupersaturation Tank

Based on the normal slurry recirculation rate in the venturi loop of 600 gpm, the slurry residence time in the oxidation tank was 11.3 minutes. The oxidation tank overflowed into a desupersaturation tank which provided an additional 4.7 minutes residence time, for a total of 16 minutes in the venturi recirculation loop. In Run 812-1A, the desupersaturation tank was removed from the recirculation system with no adverse effect on either sulfite oxidation or gypsum saturation in the venturi loop. However, the desupersaturation tank was returned to service for subsequent runs because it provided a convenient surge for both the recirculation pump and the bleed pump.

5.2.7 Effect of Oxidation Tank Agitator

Run 813-1A was made with the oxidation tank agitator turned off to determine the effect on oxidation of agitating the tank with the sparged air only. The run was ended after 7 hours because air sparging alone could not keep the solids in suspension.

5.2.8 Effect of Oxidation Tank Level

Most runs were made with an 18-foot (maximum) slurry level in the oxidation tank. However, the tank level was dropped to 14 feet (8.8 minutes oxidation tank residence time at 600 gpm) in Run 814-1A and sulfite oxidation was still maintained at 98 percent with no adverse effect on other operating conditions.

5.2.9 Effect of Flue Gas Flow Rate

Runs 801-1A through 814-1A were made at a reduced flue gas flow rate under the assumption that high SO_2 removal, in the range of 85 percent, could not be achieved at full gas rate because of the reduced pH in the venturi loop for forced oxidation.

Beginning with Run 815-1A, the flue gas flow rate was increased from the reduced rate of 25,000 acfm (at 300°F) to the maximum rate of 35,000 acfm. Air flow rate to the oxidation tank was also increased proportionally from 150 to 210 scfm to maintain the same air stoichiometry of about 1.7. SO_2 removal for Run 815-1A was 86 percent under the test conditions listed in Table 5-1, which is about 5 percentage points below SO_2 removal achieved on an identical run (Run 814-1A) at the lower flue gas flow rate. Sulfite oxidation remained high at 96 percent for Run 815-1A despite the higher sulfite throughput in the oxidation tank. All subsequent runs were made at the higher flue gas flow rate.

5.2.10 System Control

In the limestone tests with two scrubber loops, the control philosophy was to hold the venturi inlet pH (oxidation tank pH) at 5.5 by adjusting the limestone slurry feed rate to the spray tower effluent hold tank. Control in this manner proved to be difficult, and wide fluctuations were experienced in both pH and limestone stoichiometry. This was especially true when the venturi inlet pH approached the spray tower pH. For example, in Run 815-1A, the venturi inlet pH varied between 4.9 and 6.3, with corresponding fluctuations in the limestone stoichiometric ratios of 1.1 to 1.9 in the venturi loop and 1.2 to 2.7 in the spray tower loop.

In Run 815-1A, the oxidation tank level was 14 feet, which was satisfactory for forced oxidation (96 percent oxidation at an air stoichiometric ratio of 1.7). In Run 816-1A, the fluctuation in venturi inlet pH was reduced to a range of 5.2 to 5.8 with a corresponding reduction in fluctuation in limestone stoichiometry by increasing the oxidation tank level to the maximum of 18 feet. This increased hold tank residence time.

In Run 819-1B, the control philosophy was changed: the limestone stoichiometry in the spray tower was controlled at 1.6 moles calcium per mole SO_2 absorbed, and the venturi inlet pH was allowed to vary. With direct control on the spray tower stoichiometry, the fluctuation in venturi inlet pH was 5.2 to 5.8, no greater than in the previous runs with venturi inlet pH control.

On the basis of these runs, control of limestone stoichiometry in the primary scrubbing loop (spray tower) is recommended over control of pH in the oxidation loop (venturi).

5.2.11 Mist Eliminator Operation

In previous runs with limestone slurry and high fly ash loadings (Runs 805-1A through 808-1A), problems with mist eliminator plugging occurred. In these runs, the spray tower solids concentration was maintained at 15 percent. This required that the clarified liquor from the solids dewatering system be returned to the venturi loop and which allowed only enough makeup water in the spray tower system for an intermittent mist eliminator underside wash. Such a wash was inadequate at the limestone utilizations experienced in the spray tower (60 to 80 percent) and the mist eliminator plugged within a matter of days. Beginning with Run 817-1A (again with high fly ash loading), the mist eliminator was washed continuously on the bottomside at 0.4 gpm/ft^2 with clarified liquor diluted with available makeup water. Excess clarified liquor was returned to the venturi loop. This wash scheme, coupled with a sequential top wash, proved adequate and the mist eliminator no longer plugged. The continuous wash diluted the spray tower solids concentration to about 9 percent. At 9 percent solids concentration, SO_2 removal was 83 percent at 2500 ppm inlet SO_2 concentration.

In Run 818-1A, the slurry recirculation rate in the spray tower loop was increased from 1400 gpm to the maximum controlled rate of 1600 gpm. With this modification, SO_2 removal was increased to 86 percent at 2550 ppm inlet concentration.

5.2.12 Effect of Air Sparger Design

Runs 801-1A through 808-1A were made with the original air sparger which contained 130 1/8-inch diameter holes (see Section 5.1). These small holes were prone to plugging, even though the compressed air had been prehumidified to minimize the scale and solids deposits on the wet-dry interfaces. Erosion of these small holes also occurred.

In Runs 809-2A through 816-1A, a similar sparger having 40 1/4-inch diameter holes was used. This second sparger was inspected at the end of Run 813-1A after about 1800 hours of service with both lime and limestone runs, and was found to be almost completely plugged. A 3-inch diameter, 6-inch long 304 SS spool piece connecting the air line to the sparger was found to be severely corroded with holes in several spots. Most of the sparging air must have been emitted through the holes in this spool piece, probably causing the plugging of the inactive 1/4-inch diameter holes on the sparger ring. This spool piece was replaced by one with 316L SS material.

Because of the conditions mentioned above, air was emitted mainly on one side of the oxidation tank for a good portion of the testing. Air dispersion must have been accomplished primarily by the agitator. Despite this maldistribution of air, better than 95 percent sulfite oxidation was achieved in all runs affected.

Starting with Run 817-1A, the sparger ring was replaced with a 3-inch pipe with an elbow on the end to direct the air downward at the center of the tank about 3 inches above the tank bottom and one foot below the bottom agitator blade. Sulfite oxidation remained 97 percent or higher at the same air stoichiometry of about 1.7.

Based on the success with the open 3-inch pipe, it was concluded that the agitator plays a primary role in dispersing the air. The agitator used in these tests has been described in Subsection 5.1. Prehumidification of air was found unnecessary with the open 3-inch pipe.

5.2.13 Limestone Long-Term Reliability Run 819-1A

During November 1977 Run 819-1A, a one-month limestone slurry reliability run, was made with a two-scrubber-loop configuration on the venturi/spray tower system and with forced oxidation in the venturi loop. This run operated for a total of 840 hours (35 days). The run was designed to demonstrate operating reliability of the scrubber system with respect to scaling and plugging and to determine if the EPA New Source Performance Standards for SO_2 and particulate emissions could be met.

To simulate variable boiler load, the flue gas flow rate was varied between 18,000 and 35,000 acfm (4.8 and 9.4 ft/sec spray tower superficial gas velocity) as the boiler load varied between 100 and 155 MW. Flue gas with high fly ash loading was used. The venturi plug was fixed at a position to give 9 inches H_2O pressure drop across the venturi at a full 35,000 acfm flue gas flow rate. The actual venturi pressure drop ranged from 3 to 9 inches. Slurry recirculation rates were held constant at 600 gpm and 1600 gpm in the venturi and spray tower loops, respectively. The venturi inlet pH was controlled at 5.5 by controlling the limestone feed rate to the spray tower hold tank.* The oxidation tank was maintained at an 18-ft slurry level and an air flow rate of 210 scfm discharged through a 3-inch pipe.

During the run, the scrubber was shut down for 18 hours due to a boiler outage, 17-1/2 hours total for three scheduled weekly inspections, plus 3-1/2 hours of unscheduled downtime for a total of 39 hours. Based on the 3-1/2 hours of unscheduled downtime, the scrubber system had an availability of

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* As discussed in Subsection 5.2.10, this mode of control was later changed to limestone stoichiometric ratio control in the spray tower (Run 819-1B).

99.6 percent. The unscheduled downtime included 3 hours to clean a partially plugged slurry return pipe from the venturi to the oxidation tank and 1/2 hour to clean a plugged mist eliminator bottom wash nozzle.

The plugged mist eliminator nozzle was discovered after 391 hours of operation. The mist eliminator in the vicinity of the plugged nozzle was severely restricted by slurry solids (7 percent overall mist eliminator restriction.) The nozzle was cleaned but the mist eliminator was not disturbed. By the end of the run (840 hours), the mist eliminator restriction had dropped to 3 percent, demonstrating that a restricted area can be self-cleaning.

For the entire run, the SO_2 removal averaged 86 percent at 2950 ppm average inlet SO_2 concentration. This removal efficiency corresponds to an average emission of 1.1 lb SO_2/MM Btu which meets the EPA New Source Performance Standard of 1.2 lb SO_2/MM Btu. However, fluctuations to unusually high inlet SO_2 concentrations were experienced, and the standard was at times exceeded for periods greater than the three hours allowed by EPA regulations.

The outlet particulate loading ranged from 0.021 to 0.063 grain/dry scf with an average of 0.042 grain/dry scf. Assuming 30 percent excess air to the boiler, the average outlet particulate loading corresponds to 0.08 lb/MM Btu, which meets the EPA New Source Performance Standard of 0.1 lb/MM Btu. However, a few of the outlet particulate loading measurements exceeded the standard.

Sulfite oxidation averaged 98 percent during the run with the air stoichiometric ratio varying between 1.4 and 2.8 atoms oxygen/mole SO_2 absorbed. The filter cake solids concentration average 87 percent. Overall limestone utilization was 81 percent while the spray tower limestone utilization was 61 percent, demonstrating the advantage of a two-scrubber-loop system in achieving high alkali utilization.

To summarize, the operating reliability of the venturi/spray tower system in a two-scrubber-loop configuration with forced oxidation in limestone slurry service has been demonstrated with a system availability of 99.6 percent. However, under the conditions selected, the system was unable to continually meet EPA New Source Performance Standards for SO_2 and particulate emissions even though the average emissions for the run met the standards.

5.3 GENERAL OPERATING CHARACTERISTICS OF THE TWO-SCRUBBER-LOOP SYSTEM WITH FORCED OXIDATION

5.3.1 Water Balance

Because the dewatering properties of the oxidized sludge are better, less liquor leaves the system with the waste sludge (better than 80 percent solids compared with about 50 to 60 percent solids with unoxidized sludge) and the overall water balance in the slurry system is tighter. The tighter water balance results in higher dissolved solids in the slurry liquor and less available water for mist eliminator wash.

5.3.2 Control of Slurry Solids Concentration

The slurry solids concentrations in the two scrubber loops are interrelated by the system water balance. Major water loss from the scrubber system occurs in the first (venturi) scrubber loop where the flue gas is humidified. The Shawnee tests have normally been run by holding the venturi loop solids concentration at 15 percent and letting the spray tower solids concentration vary. The spray tower slurry solids concentration has depended primarily on the fly ash loading in the flue gas and on the loop to which the clarified liquor from the solids dewatering system is returned. To a certain degree, the spray tower solids concentration can be controlled by the proper distribution of the clarified liquor (usually in excess of that required for the mist eliminator wash) returned to the venturi and spray tower loops.

With limestone, low spray tower slurry solids concentration (about 5 to 6 percent) contributes to low SO_2 removal (60 to 70 percent), while the effect is much less pronounced with lime. The only adverse effect observed with lime (see Section 7) was a slight tendency to scale in the bottom part of the spray tower when the solids concentration dropped below about 7 percent.

5.3.3 Chloride Concentrations

Chlorides enter the scrubber systems as hydrochloric acid (HCl) in the flue gas. The chlorides are absorbed and concentrated in the scrubber liquor as a major component of the total dissolved solids. Chloride ion in the scrubber liquor tends to reduce the liquor pH (at constant limestone stoichiometric ratio) and consequently reduce the SO_2 removal efficiency.

Because of tighter water balance with forced oxidation, chloride ion concentration has tended to be higher than in previous operation without forced oxidation. Chloride ion concentration in the venturi loop during forced-oxidation testing ranged from 2,000 to 11,000 ppm, varying mainly with the chloride concentration of the coal burned. Chloride ion concentrations in the spray tower loop depended on where the clarified liquor from the dewatering system was returned. With clarified liquor returned to the spray tower loop, spray tower chloride ion concentration averaged about one-half the concentration in the venturi loop. With clarified liquor returned to the venturi loop, the spray tower chloride ion concentration was about one-fifth the venturi concentration. With the low spray tower chloride ion concentrations in the latter case, higher pH, and consequently higher SO_2 removal efficiency, was achieved in the spray tower loop.

5.4 SUMMARY OF FINDINGS

Following the development of forced-oxidation techniques at the IERL-RTP pilot plant on a 0.1-MW scale, forced oxidation was successfully demonstrated at the Shawnee Test Facility on 10-MW prototype scrubbers. The following summary is based on the Shawnee limestone test results from the venturi/spray tower system operating on a two-scrubber-loop configuration:

- Forced oxidation in the first of two independent scrubbing loops was successfully demonstrated in the two-scrubber-loop venturi/spray tower system with limestone slurry. Successful demonstration was culminated with a one-month reliability limestone test using flue gas with high fly ash loading.
- Under the one-month reliability test conditions of 18,000 to 35,000 acfm gas rate, 600 gpm venturi slurry rate, 1600 gpm spray tower slurry rate, 15 percent venturi slurry solids concentration, 18-ft oxidation tank level, and 5.5 oxidation tank pH, 98 percent average sulfite oxidation was achieved at air stoichiometric ratios ranging from 1.4 to 2.8 atoms oxygen/mole SO_2 absorbed. The filter cake solids concentration averaged 87 percent.

Ranges of conditions under which nearly complete sulfite oxidation (greater than 95 percent) was demonstrated were an oxidation tank pH of 4.5 to 5.5, oxidation tank level of at least 14 ft, and an air stoichiometric ratio of at least 1.5 atoms oxygen/mole SO_2 absorbed. Filter cake solids contents greater than 80 percent were consistently achieved under these conditions.

- Forced oxidation of the slurry within the scrubber loop dramatically improved the dewatering characteristics of the waste solids. Sulfite oxidation of 90 percent or higher was required for maximum improvement.
- Forced oxidation was achieved by simple air/slurry contact in the oxidation tank. Within the ranges of test conditions, an air sparger with 130 1/8-inch diameter holes, an air sparger with 40 1/4-inch diameter holes, and a 3-inch diameter pipe all seemed to give the same air/slurry contact efficiency. Air/slurry contact was primarily achieved by the two-turbine agitator operated at 56 rpm and rated at 17 brake Hp.
- Slurries with high or low fly ash loadings oxidized equally well.
- With forced oxidation, the venturi inlet slurry constantly exhibited a gypsum saturation of about 100 percent, which was below the incipient scaling level of 135 percent. This was undoubtedly caused by the abundance of gypsum crystal seeds produced by forced oxidation.
- Limestone utilization was improved with the two-scrubber-loop operation to at least 80 percent and as high as 98 percent, depending on the venturi inlet pH which averaged from 4.5 to 5.5. The venturi inlet pH was controlled by limestone addition to the spray tower hold tank.
- In limestone scrubbing, a low slurry solids concentration in the spray tower reduced the percent SO_2 removal. Furthermore, a solids concentration of 7 percent or higher was required to prevent calcium sulfite and sulfate scaling.
- Operation without the desupersaturation tank in the venturi slurry loop did not have an adverse effect on either sulfite oxidation or gypsum saturation in the venturi loop.
- Operation with the agitator turned off in the oxidation tank was not successful. Air sparging alone in the oxidation tank could not keep the solids from settling.

Section 6

VENTURI/SPRAY TOWER TWO-SCRUBBER-LOOP FORCED-OXIDATION LIMESTONE/MgO TEST RESULTS

From March 1 through May 10, 1978, a series of six runs was made in which MgO was added to the spray tower hold tank along with the limestone slurry. The primary purpose of the MgO addition was to enhance SO_2 removal efficiency in the spray tower loop by increasing the dissolved sulfite ion concentration for SO_2 scrubbing. In a two-scrubber-loop configuration, the magnesium ion concentration in the venturi loop is higher than that in the spray tower loop because of the water loss in humidifying the flue gas in the venturi loop. But because the sulfite ion is converted into nonscrubbing sulfate ion by forced oxidation, the higher magnesium ion concentration in the venturi loop does not enhance SO_2 removal in the venturi loop. The secondary purpose of the MgO addition was to determine whether the presence of magnesium ion had an effect on oxidation efficiency.

Table 6-1 presents the major test conditions and important test results for the six limestone runs with MgO addition. More detailed information for these runs is given in Appendices B through G.

Table 6-1

RESULTS OF FORCED-OXIDATION TESTS WITH TWO SCRUBBER LOOPS ON THE VENTURI/SPRAY TOWER SYSTEM USING LIMESTONE SLURRY WITH ADDED MAGNESIUM OXIDE

Major Test Conditions	820-1A	820-1B	820-1C	821-1A	822-1A	822-1B
Fly ash loading	High	High	High	High	High	High
Flue gas rate, acfm @ 300°F	35,000	35,000	35,000	35,000	35,000	35,000
Slurry rate to venturi, gpm	600	600	600	600	600	600
Slurry rate to spray tower, gpm	1600	1600	1600	0	1600	1600(4)
Venturi percent solids recirculated (controlled)	15	15	15	15	15	15
Residence times, min: Oxidation tank	11.3	11.3	11.3	11.3	11.3	11.3
Desupersaturation tank	4.7	4.7	4.7	4.7	4.7	4.7
Spray tower EHT	14.7	14.7	14.7	-	14.7	14.7
Venturi inlet (oxidation tank) pH (controlled)	5.5	-	-	5.5	-	-
Spray tower limestone stoichiometric ratio (based on solids)	-	1.6(5)	1.6(5)	-	1.6(5)	1.6(5)
Effective Mg^{++} concentration (S.T. loop), ppm	5000	5000	5000	5000	5000	5000
Venturi pressure drop, in. H_2O	9	9	9	9	9	9
Oxidation tank level, ft	18	18	18	18	18	18
Air rate to oxidation tank, scfm(1)	210	150	0	210	210	210
Clarified liquor returned to(2)	V.	V.	V.	V.	V.	V.
Selected Results						
Percent SO_2 removal	96	94	91	-	91	90
Inlet SO_2 concentration, ppm	2250	2500	2750	-	2750	2400
Spray tower percent solids recirculated	6.0	8.3	10.5	-(6)	8.0	5.6
Spray tower inlet pH	6.05	5.9	5.9	-	5.75	5.55
Spray tower limestone stoichiometric ratio (based on total slurry)	1.16	1.28	1.52	-	1.55	1.21
Spray tower inlet liquor gypsum saturation, %	100	105	90	-	100	110
Spray tower sulfite oxidation, %	30	17	20	-	21	23
Effective Mg^{++} concentration (S.T. loop), ppm	5150	4985	4700	-	4895	4845
Overall sulfite oxidation, %	98	92	36	-	97	98
Overall limestone utilization, %	92	90	82	-	79	93
Venturi inlet liquor gypsum saturation, %	130	130	145	-	125	130
Venturi inlet liquor sulfite concentration, ppm	50	950	5585	-	735	410
Air stoichiometry, atoms O/mole SO_2 absorbed	1.70	1.10	0	-	1.45	1.70
Filter cake solids, wt%(3)	85	82	63	-	85	85
Onstream hours	462	137	134	-	232	85

Notes:

(1) Air discharged downward through 3-inch diameter pipe with an open elbow at center of oxidation tank about 3 inches from tank bottom.
(2) Venturi loop (oxidation tank).
(3) Clarifier and filter used for solids dewatering in all runs.
(4) Spray tower turned off for 30 minutes every 8 hours to obtain SO_2 removal with venturi alone. Venturi SO_2 removal averaged 29%.
(5) In runs with control by spray tower stoichiometric ratio, the venturi inlet pH averaged 5.0.
(6) Run failed due to low MgO dissolution rate in spray tower effluent hold tank.

6.1 SYSTEM DESCRIPTION

The scrubber system configuration and the arrangement of the oxidation tank for the two-scrubber-loop forced-oxidation limestone tests with MgO addition were the same as those for the limestone tests without MgO addition. These are shown in Figures 5-1 and 5-2, and described in Subsection 5.1.

Dry MgO powder was fed to the spray tower hold tank by a screw feeder. The 3-inch diameter pipe with an open elbow (not shown in Figure 5-2) was used instead of the air sparger ring.

6.2 DISCUSSIONS OF TEST RUN RESULTS

6.2.1 Effect of Magnesium Ion on SO_2 Removal

Run 820-1A was made under identical conditions to Run 818-1A (see Table 5-1) except for the addition of MgO. Effective magnesium ion concentration* averaged 5150 ppm in the spray tower. The anticipated removal enhancement was achieved; the average SO_2 removal was 96 percent at 2250 ppm average inlet SO_2 concentration for the run with magnesium compared with 86 percent removal at 2550 inlet ppm for Run 818-1A without magnesium.

The spray tower inlet slurry liquor was 100 percent saturated with gypsum and no scale was observed. This condition was typical of all the tests in the limestone/MgO, forced-oxidation test block.

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* Effective magnesium ion concentration is defined as the total magnesium ion minus that magnesium ion concentration equivalent to total chlorides. Magnesium chloride has no effect on SO_2 removal.

In Run 821-1A, an attempt was made to determine the SO_2 removal in the venturi by turning off the slurry recirculation to the spray tower. Unfortunately, the MgO added to the spray tower hold tank would not dissolve without slurry recirculation and SO_2 absorption in the spray tower. The run was therefore ended.

A second attempt was more successful. Run 822-1B was an extension of Run 822-1A, in which the spray tower slurry recirculation was turned off once a shift for only 30 minutes. This short time period did not significantly upset the system balance. Average SO_2 removal in the venturi loop was found to be 29 percent, which is typical of removal efficiency with limestone slurry in the absence of magnesium ion. Thus, it has been demonstrated that magnesium ion does not enhance SO_2 removal in a scrubber loop with forced oxidation.

Run 822-1A was made in an effort to improve removal efficiency by minor changes in piping configuration to locate makeup and bleed streams at their optimum locations in the venturi slurry recirculation loop. The bleed from the spray tower loop was sent to the desupersaturation tank instead of to the oxidation tank as shown in Figure 5-1. Since the spray tower bleed stream contained higher sulfite ion concentration than the slurry liquor in the oxidation tank, introduction of this stream at a point in the venturi loop after the oxidation tank should have promoted SO_2 removal in the venturi. Also, the bleed to the solids dewatering system was taken from the oxidation tank instead of the desupersaturation tank as is shown in Figure 5-1. Improvement in SO_2 removal efficiency, if any, was too small to observe.

6.2.2 Effect of Magnesium Ion on Oxidation Efficiency

In this test block, the 3-inch pipe was used for discharging air into the oxidation tank, and an oxidation tank level of 18 feet was maintained. Runs 820-1A, B, and C were a series to explore the air stoichiometry required to achieve nearly complete oxidation. The results were as follows:

Run	Air Stoichiometric Ratio, atoms oxygen/mole SO_2 absorbed	Percent Sulfite Oxidation
820-1A	1.7	98
820-1B	1.1	92
820-1C	0	36

The oxidation efficiency for Run 820-1B was marginally acceptable at an air stoichiometric ratio of 1.1. Although sulfite oxidation averaged 92 percent, it fluctuated widely, indicating that barely enough air was available. During the last 40 hours of Run 820-1B, the air stoichiometric ratio increased to 1.3 as the inlet SO_2 concentration decreased, and the oxidation was steady at 98 percent. Thus, sulfite oxidation efficiency appeared to be unaffected, if not improved, by the addition of MgO.

Filter cake solids concentration at 98 percent oxidation averaged 85 percent, demonstrating that MgO addition does not adversely affect filtration characteristics of oxidized sludge. However, initial settling rate declined somewhat (see Subsection 22.2). This series of runs also demonstrated the effect of forced oxidation on solids filtration characteristics. Filter cake solids concentration decreased from 85 percent to 63 percent as the oxidation of sulfite decreased from 98 percent to 36 percent.

An additional observation in this series of runs was that overall limestone utilization increased from 82 to 92 percent as the air rate to the oxidation tank was increased from 0 to 210 scfm. Based on the results of Runs 820-1A and 1C, it appeared that forced oxidation promoted higher limestone utilization.

6.3 SUMMARY OF FINDINGS

The following is a summary of findings based on the test results:

- The anticipated SO_2 removal enhancement was achieved. Under typical operating conditions, average overall SO_2 removal was 96 percent at 2250 ppm average inlet SO_2 concentration with 5150 ppm effective magnesium ion concentration in the spray tower in which oxidation was not forced (Run 820-1A). Under the same operating conditions, but without MgO addition, overall SO_2 removal averaged 86 percent at 2550 ppm inlet SO_2 concentration (Run 818-1A, Table 5-1).

- Magnesium ion does not enhance SO_2 removal in a scrubber loop in which oxidation is forced, because sulfite ion is oxidized into non-scrubbing sulfate ion. SO_2 removal in the venturi loop (oxidation loop) was 29 percent (Run 822-1B with intermittent spray tower operation), which is typical of removal efficiency with limestone slurry in the absence of magnesium ion.

- The oxidation efficiency appeared to be unaffected, if not improved, by the presence of magnesium ion. Under typical conditions, sulfite oxidation was 98, 92, and 36 percent at 1.7, 1.1, and 0 air stoichiometry, respectively (Runs 820-1A, 820-1B, and 820-1C, respecitively). Nearly complete oxidation appeared to be possible at an air stoichiometric ratio as low as 1.3.

- Under the conditions tested, filter cake solids concentration at 98 percent oxidation averaged 85 percent, demonstrating that MgO addition does not adversely affect the filtration characteristics of oxidized sludge. The initial settling rate, however, is reduced when magnesium is present (see Subsection 22.2).

Section 7

VENTURI/SPRAY TOWER TWO-SCRUBBER-LOOP FORCED-OXIDATION LIME TEST RESULTS

In this section, the results of forced-oxidation lime tests with a two-scrubber-loop configuration on the venturi/spray tower system are presented. A total of 20 lime runs were made. These included 10 runs with high fly ash loading in the flue gas (4 runs from March 10 through April 1, 1977, 1 run from October 11 through October 18, 1977, and 5 runs from December 16, 1977 through February 27, 1978) and 10 runs with low fly ash loading (9 runs from June 21 through August 11, 1977 and 1 run from October 6 to October 11, 1977). Tests with high fly ash loading included a one-month lime reliability run (Run 863-1A). Except for the one-month reliability run, each test normally lasted 5 to 6 days which was judged to be sufficient time to reach kinetic equilibrium and to allow collection of adequate run data.

In many aspects, the operating characteristics and results of the two-scrubber-loop forced-oxidation lime tests were similar to those of limestone tests presented in Section 5.

Table 7-1 summarizes the major test conditions and important test results for the two-scrubber-loop forced-oxidation lime runs. Additional detailed information for these runs can be found in Appendices B through G.

Table 7-1

RESULTS OF TWO-SCRUBBER-LOOP FORCED-OXIDATION LIME TESTS ON THE VENTURI/SPRAY TOWER SYSTEM

Major Test Conditions	851-1A	852-1A	853-1A	854-1A	855-1A	856-1A	857-1A	858-1A
Fly ash loading	High	High	High	High	Low	Low	Low	Low
Gas rate, acfm @ 300°F	25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000
Venturi liquor rate, gpm	600	160	600	600	600	600	600	600
Spray tower liquor rate, gpm	1400	1400	1400	1400	1400	1400	1400	1400
Venturi percent solids recirculated (controlled)	15	15	15	15	15	15	15	8
Residence times, min: Oxidation tank	11.3	42	11.3	11.3	11.3	11.3	11.3	11.3
Desupersaturation tank	4.7	17.7	4.7	4.7	4.7	4.7	4.7	4.7
Spray tower EHT	18	18	18	18	18	18	18	18
Venturi inlet (oxidation tank) pH (controlled)	4.5	≥4.5(2)	≥4.5(3)	5.2	4.5(4)	5.0	5.5	5.5
Spray tower inlet pH (controlled)	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
Venturi pressure drop, in. H_2O	9	(min)	(min)	9	9	9	9	9
Oxidation tank level, ft	18	18	18	18	18	18	18	18
Air rate to oxidation tank, scfm	150(5)	150(5)	150(5)	150(5)	150(6)	150(6)	150(6)	150(6)
Clarified liquor returned to(8)	V. & S.T.	V. & S.T.	S.T.	S.T.	S.T.	S.T.	S.T.	V.
Selected Results								
Percent SO_2 removal	78	70	77	82	83	88	84	83
Inlet SO_2 concentration, ppm	3300	3400	3450	3150	2350	2500	2650	2750
Spray tower percent solids recirculated	6.0	8.3	6.4	6.1	7.3	7.9	7.9	15.2
Spray tower lime stoichiometric ratio	1.13	1.13	1.14	1.15	1.14	1.16	1.14	1.13
Spray tower inlet liquor gypsum saturation, %	80	50	80	55	95	90	90	85
Spray tower sulfite oxidation, %	15	13	14	11	18	12	11	14
Overall sulfite oxidation, %	97	83	97	96	98	97(9)	97	97
Overall lime utilization, %	98	96	95	97	98	98	99	98
Venturi inlet liquor gypsum saturation, %	95	105	100	100	105	95	100	110
Venturi inlet liquor sulfite concentration, ppm	39	22	35	35	24	36(9)	64	20
Air stoichiometry, atoms O/mole SO_2 absorbed	1.45	1.55	1.40	1.40	1.90	1.65	1.65	1.60
Filter cake solids, wt%(10)	81	73	78	79	75(11)	83(11)	78	81
Onstream hours	110	74	161	166	158	209	128	162

Note: Footnotes for this table are listed at the end of Table 7-1 (continued).

Table 7-1 (continued)

RESULTS OF TWO-SCRUBBER-LOOP FORCED-OXIDATION LIME TESTS ON THE VENTURI/SPRAY TOWER SYSTEM

Major Test Condtions	859-1A	859-1B	859-1C	859-1D	860-1A	861-1A
Fly ash loading	Low	Low	Low	Low	Low	Low
Gas rate, acfm @ 300^0F	25,000	25,000	25,000	25,000	25,000	25,000
Venturi liquor rate, gpm	600	600	600	600	600	600
Spray tower liquor rate, gpm	1400	1400	1400	1400	1400	1400
Venturi percent solids recirculated (controlled)	15	15	15	15	15	15
Residence times, min: Oxidation tank	11.3	11.3	11.3	11.3	11.3	11.3
Desupersaturation tank	4.7	4.7	4.7	4.7	4.7	4.7
Spray tower EHT	18	18	18	18	12.6	18
Venturi inlet (oxidation tank) pH (controlled)	5.5	5.5	5.5	5.5	5.5	5.5
Spray tower inlet pH (controlled)	8.0	8.0	8.0	8.0	8.0	8.0
Venturi pressure drop, in. H_2O	9	9	9	9	9	9
Oxidation tank level, ft	18	18	18	18	18	18
Air rate to oxidation tank, scfm	135(6)	150(6)	100(6)	0	150(6)	150(7)
Clarified liquor returned to(8)	S.T.	S.T.	S.T.	S.T.	S.T.	S.T.
Selected Results						
Percent SO_2 removal	92	92	92	93	95	92
Inlet SO_2 concentration, ppm	2950	2700	2700	2600	2200	2700
Spray tower percent solids recirculated	7.2	7.6	7.3	7.1	7.0	7.3
Spray tower lime stoichiometric ratio	1.16	1.16	1.15	1.17	1.18	1.16
Spray tower inlet liquor gypsum saturation, %	60	90	90	50	70	90
Spray tower sulfite oxidation, %	10	12	20	10	10	19
Overall sulfite oxidation, %	76	99	69	30	99	98
Overall lime utilization, %	97	99	96	90	99	99
Venturi inlet liquor gypsum saturation, %	95	105	105	115	100	95
Venturi inlet liquor sulfite concentration, ppm	99	33	82	85	20	35
Air stoichiometry, atoms O/mole SO_2 absorbed	1.20	1.50	1.0	0	1.75	1.50
Filter cake solids, wt%(10)	74	78	71	55	82	86
Onstream hours	115	70	120	72	133	117

Table 7-1 (continued)

RESULTS OF TWO-SCRUBBER-LOOP FORCED-OXIDATION LIME TESTS ON THE VENTURI/SPRAY TOWER SYSTEM

Major Test Conditions	862-1A	863-1A	864-1A	865-1A	866-1A	867-1A
Fly ash lading	High	High	High	High	High	High
Gas rate, acfm @ 300^{o}F	35,000	(1)	35,000	35,000	35,000	35,000
Venturi liquor rate, gpm	600	600	600	600	600	600
Spray tower liquor rate, gpm	1400	1600	1600	1600	1600	1600
Venturi percent solids recirculated (controlled)	15	15	15	15	15	15
Residence times, min: Oxidation tank	11.3	11.3	11.3	6.3	6.3	8.8
Desupersaturation tank	4.7	4.7	4.7	4.7	4.7	4.7
Spray tower EHT	18	14.7	14.7	14.7	14.7	14.7
Venturi inlet (oxidation tank) pH (controlled)	5.5	5.5	5.5	5.5	5.5	5.5
Spray tower inlet pH (controlled)	8.0	7.8	7.8	7.8	7.8	7.8
Venturi pressure drop, in. H_2O	9	≤9	9	9	9	9
Oxidation tank level, ft	18	18	18	10	10	14
Air rate to oxidation tank, scfm	210$^{(7)}$	210$^{(7)}$	210$^{(7)}$	290/210$^{(7)}$	350$^{(7)}$	210$^{(7)}$
Clarified liquor returned to$^{(8)}$	V.	V. & S.T.	V. & S.T.	V. & S.T.	V. & S.T.	V. & S.T.
Selected Results						
Percent SO_2 removal	85	88	94	89	94	89
Inlet SO_2 concentration, ppm	2650	2950	2250	2300	1700/2400	2300
Spray tower percent solids recirculated	17.3	10.4	9.5	10.1	9.9	11.8
Spray tower lime stoichiometric ratio	1.11	1.11	1.13	1.10	1.15	1.12
Spray tower inlet liquor gypsum saturation, %	85	100	100	95	90	85
Spray tower sulfite oxidation, %	18	21	24	26	26	20
Overall sulfite oxidation, %	97	97	98	89	98/81	98
Overall lime utilization, %	98	98	99	98	98	99
Venturi inlet liquor gypsum saturation, %	105	105	100	100	95	90
Venturi inlet liquor sulfite concentration, ppm	30	35	25	65	40	40
Air stoichiometry, atoms O/mole SO_2 absorbed	1.65	1.40-2.75	1.75	2.10	3.85/2.70	1.80
Filter cake solids, wt%$^{(10)}$	86	85	85	80	81	86
Onstream hours	162	779	115	254	159	137

Notes:

(1) Gas rate was varied from 18,000 to 35,000 acfm to follow the boiler load.
(2) Actual pH range was 4.6-6.2 (avg. 5.6).
(3) Actual pH range was 4.3-5.2 (avg. 4.8).
(4) Actual average pH was 4.7.
(5) Used a sparger ring located 6 inches from tank bottom. The sparger ring had 130 1/8-inch holes on the bottom side.
(6) Used a sparger ring located 6 inches from tank bottom. The sparger ring had 40 1/4-inch holes on the bottom side.
(7) Air discharged downward through a 3-inch diameter pipe with an open elbow at center of oxidation tank about 3 inches from tank bottom.
(8) Spray tower loop (effluent hold tank) or venturi loop (oxidation tank).
(9) Excluded a period 7/2/77-7/5/77 in which oxidation dropped to as low as 62% for unknown reason.
(10) Clarifier and filter in series used for solids dewatering in all runs.
(11) Intermittent filter operation.

7.1 SYSTEM DESCRIPTION

The scrubber system flow configuration and the arrangement of the oxidation tank for the two-scrubber-loop forced-oxidation lime tests were essentially the same as those for the limestone tests, which have been shown in Figures 5-1 and 5-2 and described in Subsection 5.1.

There were only two minor changes in flow configuration when lime, instead of limestone, was used. In the lime tests, fresh lime slurry (alkali) was added to both scrubber loops to maintain pH control. However, fresh limestone slurry was added only to the spray tower loop in the limestone tests. In these tests, sufficient residual undissolved limestone remained to provide pH control in the venturi loop. In lime testing, the clarified liquor from the solids dewatering system was never returned to the mist eliminator wash circuit as was done in limestone testing. Because of normally high alkali utilization (see Section 8, Reference 3), intermittent top and bottom mist eliminator wash with makeup water only was sufficient to keep the mist eliminator clean during lime tests.

7.2 DISCUSSIONS OF TEST RUN RESULTS

7.2.1 pH Control During Initial Runs

During Run 851-1A, the first lime run with high fly ash loading (see Table 7-1), it became apparent that pH control in the venturi loop was different with lime than with limestone. In limestone testing, the venturi inlet pH was maintained by adding excess limestone to the spray tower loop. Residual limestone in the bleed from the spray tower loop to the venturi provided sufficient buffer to keep the pH from dropping rapidly in the venturi loop.

Under normal venturi operating conditions with lime (600 gpm slurry flow rate to the venturi, 9 inches H_2O pressure drop), pH could not be maintained in the venturi by lime addition to the spray tower loop alone without raising the pH excessively in the spray tower. After about 30 hours of operation of Run 851-1A, the control method was changed to provide separate control of the venturi and spray tower inlet pH at 4.5 and 8.0, respectively, by independent lime feed to the venturi and spray tower loops.

In Runs 852-1A and 853-1A, unsuccessful attempts were made to control the venturi inlet pH by changing the venturi slurry recirculation rate and venturi pressure drop. The tests were made primarily to see whether independent lime addition to the venturi loop could be avoided. Operation in this manner proved to be unstable, and sulfite oxidation dropped drastically when the venturi inlet pH increased to above 6.

Finally, in Run 854-1A, the venturi inlet pH control method was changed back to that with an independent lime feed to the venturi loop. The venturi and spray tower inlet pH's were controlled at 5.2 and 8.0, respectively, by separate lime feed pumps. This mode of pH control provided smooth operation. Sulfite oxidation averaged 96 percent for Run 854-1A, and SO_2 removal was 82 percent at 3150 ppm average inlet SO_2 concentration.

7.2.2 Effect of Oxidation Tank pH

After lime Run 854-1A, lime testing was interrupted by a scheduled Boiler No. 10 maintenance outage from April 2 through June 13, 1977. Flue gas with low fly ash loadings (0.04 to 0.20 grain/dry scf) was used when lime testing resumed.

As with limestone, runs were made (Runs 855-1A through 857-1A) to determine if oxidation tank pH affected sulfite oxidation. Over the pH range of 4.5 to 5.5, no adverse effect on oxidation was observed. During these tests, percent SO_2 removal ranged from 83 to 88 percent at about 2500 ppm inlet SO_2 concentration. Subsequent runs were made at a venturi inlet pH of 5.5.

During Run 856-1A, sulfite oxidation dropped for unknown reasons to as low as 62 percent and then gradually recovered to 98 percent in a three-day period (July 2 to 5, 1977). This drop in oxidation was also observed in the same time period on the TCA system (Run 802-2A, Section 12). Although the reason for this drop in oxidation was never determined, it was postulated that the presence of oxidation inhibitors (possibly introduced by makeup water from the Ohio River) or a drop in concentrations of oxidation catalysts (e.g., trace metals and organic matter) might have been the cause.

7.2.3 Effect of Venturi Slurry Solids Concentration

In Run 858-1A, the effect of dropping the venturi loop slurry solids concentration from 15 to 8 percent (reduced oxidation tank residence time based on system bleed rate) was investigated. Sulfite oxidation was not affected and remained high at 97 percent.

In this run, clarified liquor from the dewatering system and makeup water in excess of the mist eliminator wash were added to the venturi loop rather than to the spray tower. This resulted in a buildup of the spray tower slurry solids concentration from 8 to 15 percent. With lime slurry, the higher spray tower slurry solids concentration did not improve SO_2 removal, as had been observed with limestone slurry (see Run 805-1A, Section 5). This difference between lime and limestone was expected, because lime is more soluble than limestone.

Subsequent runs with low fly ash loading were made at 15 percent venturi slurry solids and with clarified liquor returned to the spray tower loop.

7.2.4 Effect of Air Rate to the Oxidation Tank

As with limestone, tests were made to determine the minimum air required for nearly complete sulfite oxidation. Results were as follows:

Effect of Air Stoichiometry on Sulfite Oxidation for Lime Slurry (5.5 pH) with Low Fly Ash Loading

Run	Air Rate, scfm	Air Stoichiometry, atoms oxygen/mole SO_2 abs.	Percent Sulfite Oxidation
859-1B	150	1.5	99
859-1A	135	1.2	76
859-1C	100	1.0	69
859-1D	0	0	30

In these tests, the break from nearly complete oxidation occurred between 1.2 and 1.5 air stoichiometry, somewhat higher than with limestone but still excellent. In the limestone tests, a sparger ring with 130 1/8-inch holes was used. In the lime tests, a ring with 40 1/4-inch holes was used. Both of these spargers plugged, as has been discussed in Section 5. Oxidation tank pH was higher in the lime tests (5.5) than in the limestone tests (4.5).

Any combination of these differences may have contributed to the increase in air stoichiometry required for near complete oxidation.

7.2.5 Effect of Spray Tower Hold Tank Residence Time

In Run 860-1A, the spray tower hold tank residence time was dropped from 18 minutes to 12.6 minutes, from a tank level of 10 feet, 9 inches to one of 7 feet, 6 inches. The higher tank level had been used previously to keep the bleed pump taking suction from the spray tower downcomer from cavitating. Before this run, the suction point on the downcomer was lowered to allow lower tank level and more reasonable residence time.

This change had no adverse effect on sulfite oxidation or SO_2 removal. Sulfite oxidation was 99 percent and SO_2 removal was 95 percent at 2200 ppm inlet SO_2 concentration.

7.2.6 Effect of Air Sparger Design

Following lime Run 860-1A, a series of limestone tests with low fly ash loading was conducted (see Runs 809-1A through 816-1A, Section 5). Lime testing resumed on October 6, 1977. Starting with lime Run 861-1A, a 3-inch diameter pipe with an open elbow was used to introduce air into the oxidation tank. Previous lime runs had used either a sparger with 130 1/8-inch holes (Runs 851-1A through 854-1A) or a sparger with 40-1/4 holes (Runs 855-1A through 860-1A). Some plugging and erosion of the holes was experienced with these rings.

As with limestone tests (see Subsection 5.2.12), oxidation efficiency during lime tests was as good with the 3-inch air pipe as with the spargers. For example, in Run 861-1A with the air pipe, 98 percent sulfite oxidation was achieved at an air stoichiometry of 1.5 atoms oxygen/mole SO_2 absorbed. Based on the success with the open 3-inch pipe, it was concluded that, as with limestone runs, the agitator plays a primary role in dispersing the air. The agitator used in the oxidation tank has been described in Subsection 5.1.

7.2.7 Control of Spray Tower Slurry Solids Concentration

As has been mentioned in Subsection 5.3.2, the slurry solids concentrations in the scrubber loops are interrelated by the system water balance. Virtually all the fly ash is captured in the slurry in the venturi loop so that the spray tower slurry is essentially free of fly ash. To compensate for the fly ash, the venturi loop is normally controlled at a higher slurry solids concentration than the spray tower loop.

Slurry solids concentration in the venturi scrubber loop was controlled at 15 weight percent in a majority of the lime runs. Slurry solids concentration in the spray tower varied from 6 percent to almost 20 percent, depending on whether the clarified liquor from the dewatering system was returned to the venturi loop or the spray tower loop. Beginning with Run 863-1A, the returning clarified liquor was split between the two scrubber loops to control the spray tower slurry solids concentration at about 10 percent. This solids level was a compromise between low solids (below about 7 percent), where scaling and a drop in SO_2 removal are experienced, and high solids (above about 15 percent), where it becomes more difficult to keep the mist eliminator clean.

7.2.8 Effect of Flue Gas Flow Rate

Runs 851-1A through 861-1A were made at a reduced flue gas flow rate of 25,000 acfm (at 300°F) because it was assumed that forced oxidation would reduce SO_2 removal efficiency in the venturi loop at lower pH to the extent that an overall SO_2 removal efficiency of at least 80 percent could not be achieved. This proved not to be the case. Beginning with Run 862-1A, the flue gas flow rate was increased to the maximum achievable of 35,000 acfm (at 300°F), which corresponds to a spray tower superficial velocity of 9.4 ft/sec. In this run SO_2 removal averaged 85 percent at 2650 ppm inlet SO_2 concentration. Air flow rate to the oxidation tank was increased proportionally with flue gas from 150 scfm to 210 scfm to maintain the same air stoichiometry. Sulfite oxidation for Run 862-1A remained high at 97 percent despite the higher sulfite throughput in the oxidation tank.

7.2.9 Effect of Spray Tower Slurry pH on Sulfite Scaling

The pH drop across the spray tower depends on the SO_2 removal and the inlet SO_2 concentration. In Runs 851-1A through 862-1A, the spray tower inlet slurry liquor pH was controlled at 8.0. In some of these runs, when the inlet SO_2 concentration was low (corresponding to low SO_2 make-per-pass), this level of inlet pH resulted in an outlet pH approaching 6.0 and caused sulfite scaling, especially in those runs at low slurry solids concentration. It has been generally observed that sulfite scaling does not occur if the spray tower outlet pH stays below about 5.5. Therefore, during Run 863-1A, the inlet pH was adjusted downward slightly at 7.8. In this run and in subsequent runs, small patches of scale were observed to appear and disappear in a cyclic manner.

This cyclic appearance of scale did not interfere with scrubber operation. No effect on SO_2 removal was discernible as a result of the slight adjustment in inlet pH.

This slight adjustment in pH is significant in that it demonstrates the need for good pH control in commercial installations. This adjustment is one of several operating adjustments that can be made to eliminate a scaling problem.

7.2.10 Effect of Oxidation Tank Level

In Runs 864-1A through 867-1A, the effect of oxidation tank slurry level (and consequently air and slurry residence times) was explored. In these tests, air was discharged into the bottom of the oxidation tank through an open 3-inch pipe as previously described. Major test conditions are listed in Table 7-1. All four runs were made at an oxidation pH of 5.5. The effect of the tank level is summarized below:

Run No.	Oxidation Tank Level, ft	Air Stoichiometry, atoms oxygen/mole SO_2 abs.	Percent Sulfite Oxidation
864-1A	18	1.75	98
867-1A	14	1.80	98
865-1A	10	2.10	89
866-1A	10	3.85/2.70	98/81

Oxidation efficiency was high at 18- and 14-foot tank levels but dropped off at a 10-foot level. In Run 866-1A, high oxidation efficiency was achieved at a 10-foot tank level by increasing air stoichiometry. Part of Run 866-1A was made at lower air stoichiometry, with subsequent loss in oxidation efficiency.

These runs demonstrated that 98 percent sulfite oxidation can be achieved at 14- to 18-foot tank levels at an air stoichiometry of 1.8 atoms oxygen/mole SO_2 absorbed. At a 10-foot tank level, an air stoichiometry approaching 4 is required.

It must be pointed out that the oxidation at a 10-foot tank level is not directly comparable with those at 14 and 18 feet because the top turbine of the agitator is located at the 11-foot level. In 10-foot slurry level tests, the top turbine is not in contact with the slurry, and a different agitation pattern results.

Filter cake solids concentration during these tests was about 85 percent when sulfite oxidation was 98 percent. In test periods when oxidation efficiency dropped below 90 percent, the filter cake solids concentration tended toward a lower range of 80 percent.

7.2.11 Lime Long-Term Reliability Run 863-1A

From mid-December 1977 through mid-January 1978, Run 863-1A, a one-month lime slurry reliability run, was made with the venturi/spray tower system in a two-scrubber-loop configuration with forced oxidation in the venturi scrubber loop. Onstream operation for this run totaled 779 hours (32 days). As with the limestone reliability Run 819-1A (see Subsection 5.2.13), the run was designed to demonstrate operating reliability of the scrubber system with respect to scaling and plugging, and to determine if the EPA New Source Performance Standards for SO_2 and particulate emissions could be met.

As in the limestone reliability test, the flue gas flow rate was varied between 18,000 and 35,000 acfm (4.8 and 9.4 feet/sec spray tower superficial gas velocity) as the boiler load varied between 100 and 155 MW. Flue gas with high fly ash loading was used. The venturi plug was fixed at a position to give 9 inches H_2O pressure drop across the venturi at a full 35,000 acfm flue gas flow rate. The actual venturi pressure drop ranged from 2 to 9 inches H_2O. The slurry recirculation rates to the venturi and spray tower were held constant at 600 and 1600 gpm, respectively. The venturi inlet pH was controlled at 5.5. The oxidation tank level was 18 feet, and the oxidation air flow rate was 210 scfm discharged through a 3-inch pipe. As previously discussed, the spray tower inlet slurry pH was adjusted downward from 8.0 to 7.8 to eliminate an observed sulfite scale buildup.

During the run, the scrubber was shut down for a total of 57 hours; 46 hours were due to boiler outages, 7-1/2 hours were for scheduled scrubber inspections, and 3-1/2 hours were unscheduled downtime. This resulted in a scrubber availability of 99.6 percent, excluding the interruptions due to boiler outages and the scheduled inspections. The unscheduled downtime included 2 hours for mist eliminator cleaning and 1-1/2 hours for air compressor repair.

Average SO_2 removal for the entire run was 88 percent at 2950 ppm average inlet SO_2 concentration. This corresponds to an average emission of 0.9 lb SO_2/MM Btu, well within the EPA standard of 1.2 lb SO_2/MM Btu. However, because of unusually wide fluctuations in inlet SO_2 concentration and slow system response time, the SO_2 emissions at times exceeded the EPA standard for periods greater than the three hours allowed by EPA regulations.

The fluctuations in inlet SO_2 concentration, ranging up to 4700 ppm at one point, resulted from the wide variety of coals being burned during the 1977-78 coal strike. Normally, inlet SO_2 concentration ranges between 2000 and 3000 ppm. These high SO_2 concentrations were beyond the removal capacity of the venturi/spray tower system with its limited slurry recirculation rates (liquid-to-gas ratios of 21 and 57 gal/Mcf at a 35,000 acfm full gas flow rate in the venturi and spray tower, respectively).

Average particulate loading was 0.046 grain/dry scf (0.034 to 0.059 range), corresponding to an average emission of 0.09 lb particulate/MM Btu (assuming 30 percent boiler excess air). This figure is below the EPA emission standard of 0.10 particulate/MM Btu. However, in a few cases, the EPA standard was exceeded.

Sulfite oxidation averaged 97 percent during the run, with the air stoichiometric ratio varying between 1.4 and 2.8 atoms oxygen/mole SO_2 absorbed. The filter cake was excellent throughout the run, and solids concentration averaged 85 percent. Lime utilization was 90 percent in the spray tower and 98 percent overall, reflecting the high utilization to be expected in a two-scrubber-loop system.

At the first scheduled inspection after 160 operating hours, the mist eliminator was found to be 15 percent restricted by solids. After a review of the history of the mist eliminator exposure, the restriction was attributed to excess calcium carbonate from the previous limestone run (limestone stoichiometric ratio of 1.65 in the spray tower) and a failure to activate the intermittent underwash for the first eight hours of the reliability run. At the beginning of the reliability run, the mist eliminator underwash had been changed from continuous with diluted clarified liquor (needed for the limestone run conditions) to intermittent with makeup water (1.5 gpm/ft^2 for 6 minutes every 4 hours -- satisfactory for lime runs). The mist eliminator was cleaned and the run was continued. This mishap broke a record of 4138 hours of operation under widely varying conditions without cleaning the mist eliminator.

At subsequent inspections at 399 operating hours and at the end of the run, the mist eliminator was entirely clean.

In summary, the operating reliability of the venturi/spray tower system in a two-scrubber-loop configuration with forced oxidation in lime slurry service has been demonstrated with a system availability of 99.6 percent. However, under the conditions selected, the system was unable to continually meet EPA New Source Performance Standards for SO_2 and particulate emissions even though the average emissions for the run met the standards.

7.2.12 General Operating Characteristics of the Two-Scrubber-Loop Forced-Oxidation System with Lime Slurry

The operating characteristics of the two-scrubber-loop forced-oxidation system with lime slurry was generally the same as that with limestone slurry The operating characteristics with limestone slurry have been discussed in Subsection 5.3.

A major difference for the lime slurry was that separate control of the venturi and spray tower inlet pH was required by independent lime feed to each of the scrubber loops. This method of pH control for lime was necessary to avoid wide fluctuations in the venturi and spray tower pH (see Subsection 7.2.1) because lime slurry is less buffered than limestone slurry. With limestone slurry, the venturi inlet pH could be controlled by adding excess limestone to the spray tower hold tank only.

7.3 SUMMARY OF FINDINGS

The operating characteristics and test results of the two-scrubber-loop forced-oxidation lime tests were similar to those of limestone tests in many respects. The same conclusions could often be drawn for both lime and limestone operations (see Subsection 5.4).

Findings from lime testing on the venturi/spray tower system included the following:

- Forced oxidation of sulfite to sulfate in the first of two independent scrubbing loops was successfully demonstrated in the two-scrubber-loop venturi/spray tower system with lime slurry. Successful demonstration of the forced oxidation was culminated with a one-month reliability lime test using flue gas with high fly ash loading.
- Under the one-month reliability test conditions of an 18,000 to 35,000 acfm gas rate, 600 gpm venturi slurry rate, 1600 gpm spray tower slurry rate, 15 percent venturi slurry solids concentration, 18-foot oxidation tank level, and 5.5 oxidation tank pH, an average sulfite oxidation of 97 percent was achieved with air stoichiometric ratios ranging from 1.40 to 2.75 atoms oxygen/mole SO_2 absorbed. The filter cake solids concentration averaged 85 percent.
- As with limestone tests, ranges of conditions under which nearly complete sulfite oxidation (greater than 95 percent) was demonstrated were an oxidation tank pH of 4.5 to 5.5, oxidation tank level of at least 14 feet, and an air stoichiometry of at least 1.5 atoms oxygen/mole SO_2 absorbed. Filter cake solids contents of about 80 percent or higher were achieved under these conditions.
- The degree of sulfite oxidation was not affected when the venturi slurry solids concentration was dropped from the normal

15 percent to 8 percent by weight.

- Oxidation efficiency appeared to drop off at pH's greater than about 6.
- Sulfite oxidation of 90 percent or higher was required to obtain maximum improvement in waste solids dewatering characteristics.
- As with limestone tests, forced oxidation was achieved by simple air/ slurry contact in the oxidation tank. Within the ranges of test conditions, an air sparger with 130 1/8-inch diameter holes, an air sparger with 40 1/4-inch diameter holes, and a 3-inch diameter pipe all seemed to give the same air/slurry contact efficiency. Air/slurry contact was primarily achieved by the two-turbine agitator operated at 56 rpm and rated at 17 brake Hp.
- Slurries with high and low fly ash loadings oxidized equally well.
- Independent lime addition to both scrubber loops was necessary to have smooth venturi and spray tower inlet pH control.
- As in the limestone tests, the venturi inlet slurry liquor constantly exhibited a gypsum saturation level of about 100 percent when oxidation was forced within the venturi loop. This was probably the result of the abundance of gypsum crystal seeds produced by forced oxidation. The 100 percent saturation level is well below the incipient scaling level of 135 percent.
- Lime utilization in the spray tower averaged about 88 percent. Overall lime utilization averaged 98 percent, demonstrating the advantage of a two-scrubber loop system.
- Spray tower scaling (mostly by calcium sulfite) may occur when the recirculated slurry solids concentration in the spray tower drops below about 7 percent (low fly ash loading). This is especially true when the spray tower outlet pH stays above about 5.5.
- Intermittent mist eliminator wash on both the top and bottom sides with makeup water was enough to keep the mist eliminator clean, with a lime stoichiometry of 1.10 to 1.18 in the spray tower.
- Oxidation efficiency did not appear to be affected when the oxidation tank level was dropped from 18 to 14 feet at 1.8 air stoichiometry and 5.5 pH. At a 10-ft tank level, an air stoichiometry approaching 4 was required to obtain nearly complete oxidation.

Section 8

VENTURI/SPRAY TOWER BLEED STREAM OXIDATION LIMESTONE/MgO TEST RESULTS

Forced oxidation within the scrubber loop requires a compromise between the conditions needed for good oxidation (low pH with an optimum of 4.5) and those needed for good SO_2 removal (high pH). Such would not be the case if it were possible to oxidize the slurry bleed stream by simple air/slurry contact. Bleed stream oxidation would be especially desirable for retrofitting the forced-oxidation system to existing commercial lime/limestone flue gas desulfurization facilities because it would have no effect on the scrubber operation.

However, tests at the IERL-RTP pilot plant (Reference 6) showed that forced oxidation of a scrubber bleed stream required higher air stoichiometry compared with oxidation within the scrubbing loop (5.3 versus 3.5). Furthermore, the properties of the oxidized solids were inferior to those obtained by oxidation within the scrubbing loop.

Bleed stream oxidation tests conducted at the Shawnee Test Facility in March 1977 confirmed these observations. Tests were conducted using a Penberthy ELL-3 air eductor. A 120-gpm slurry stream was pumped from the oxidation tank through the air eductor, which aspirated air at 30 to 57 scfm and discharged the air/slurry mixture back to the oxidation tank. Bleed rate to the oxidation tank was about 3 gpm. Three tests were conducted with limestone slurry with a high fly ash loading which was bled from the TCA system and three tests were conducted with lime slurry with a low fly ash loading which was bled from the venturi/spray tower system.

In all tests, the pH of the slurry recirculating through the eductor rose to a level of 7 to 8 because of the dissolution of residual alkali and no oxidation occurred. Evidently, the dissolution rate of solid calcium sulfite ($CaSO_3$) at such a pH level was too slow for significant sulfite oxidation to occur.

In a series of batch oxidation tests conducted on the same equipment during the boiler outage of April-May 1977, complete oxidation was achieved by continuously adding 93 percent sulfuric acid to maintain a slurry pH of 5 to 6 in the oxidation tank. Typically, the oxidation rate was about 2.5×10^{-4} g-mole sulfite oxidized per liter per minute. However, sulfuric acid addition would not seem to be a commercially desirable procedure.

Only marginal improvement was observed in slurry settling rate, settled density, and filter cake solids content of the oxidized slurry from the batch tests. The marginal improvement is in agreement with the results observed in the IERL-RTP pilot plant bleed stream tests.

Despite the generally unfavorable results, batch oxidation tests at the Shawnee Laboratory indicated that nearly complete sulfite oxidation could be achieved by simple air sparging of lime or limestone slurry when magnesium ion was present in concentrations of 1000 ppm or higher. Magnesium ion apparently has two effects: it tends to buffer the pH rise from dissolving residual alkali in the waste slurry solids, and it tends to promote dissolved sulfite availability, allowing oxidation to take place at a higher pH.

Starting in mid-May 1978, bleed stream forced oxidation with limestone slurry and added MgO was successfully demonstrated in a month-long series of tests on the venturi/spray tower system. Oxidized slurry from these tests had good dewatering properties, and filter cake solids concentration averaged about 84 percent. Thus, it is commercially feasible to improve the quality and reduce the volume of waste solids in installations that incorporate magnesium ion in the slurry liquor by simple air/slurry contact of the bleed stream.

8.1 SYSTEM DESCRIPTION

The venturi/spray tower system was arranged as shown in Figure 8-1 for the bleed stream oxidation tests. Both the venturi and the spray tower slurries discharged into a single hold tank to which limestone and MgO were fed. A bleed stream was taken from the spray tower downcomer to take advantage of the low pH at that point. The bleed stream was discharged to the oxidation tank. All tests were conducted at an 18-ft oxidation tank level. Bleed from the oxidation tank was dewatered by a clarifier and a filter in series.

8.2 DISCUSSIONS OF TEST RUN RESULTS

Four bleed stream oxidation runs were made on the venturi/spray tower system using limestone with added MgO. All tests were conducted with approximately 5000 ppm effective magnesium ion concentration in the slurry liquor. Major test results are reported in Table 8-1. More detailed information for these tests can be found in Appendices B through G. Percent SO_2 removal was high

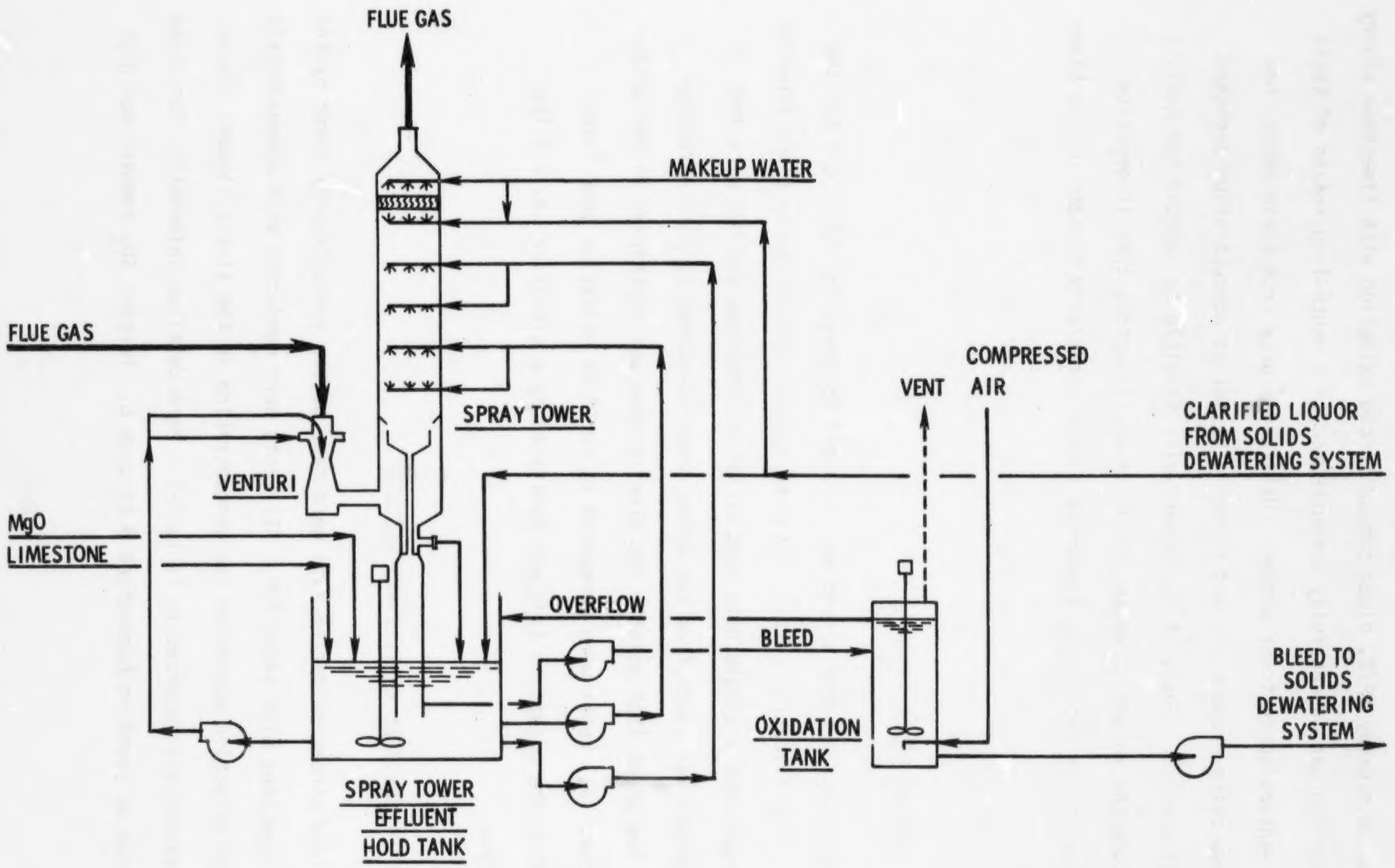

FLUE GAS
MAKEUP WATER
FLUE GAS
SPRAY TOWER
VENTURI
MgO
LIMESTONE
VENT
COMPRESSED AIR
CLARIFIED LIQUOR FROM SOLIDS DEWATERING SYSTEM
OVERFLOW
BLEED
OXIDATION TANK
BLEED TO SOLIDS DEWATERING SYSTEM
SPRAY TOWER EFFLUENT HOLD TANK

Figure 8-1. Flow Diagram for Bleed Stream Oxidation in the Venturi/Spray Tower System

Table 8-1

RESULTS OF FORCED-OXIDATION TESTS ON THE VENTURI/SPRAY TOWER BLEED STREAM USING LIMESTONE SLURRY WITH ADDED MAGNESIUM OXIDE

Major Test Conditions	823-1A	824-1A	825-1A	826-1A
Fly ash loading	High	High	High	High
Flue gas rate, acfm @ 300°F	18,000	35,000	18,000	26,500(3)
Slurry rate to venturi,gpm	600	600	600	600
Slurry rate to spray tower, gpm	1600	1600	1600	1600
Percent solids recirculated (controlled)	15	15	15	15
EHT residence time, min.	11.2	11.2	11.2	11.2
Spray tower inlet pH (controlled)	5.3	-	-	-
Scrubber limestone stoichiometric ratio (controlled)(based on solids)	-	1.9	1.4	1.4
Effective Mg^{++} concentration, ppm	5000	5000	5000	5000
Venturi pressure drop, in. H_2O	9	9	9	9
Oxidation tank level, ft	18	18	18	18
Air rate to oxidation tank, scfm(1)	110	210	110	210
Recycle flow from oxidation tank to EHT, gpm	30	30	0	0
Selected Results				
Percent SO_2 removal	94	88	95	89
Inlet SO_2 concentration, ppm	2600	2600	2500	2750
Scrubber percent solids recirculated	13.3	14.1	14.7	15.2
Scrubber inlet liquor pH	5.25	5.25	5.45	5.35
Oxidation pH	6.30	5.90	5.65	5.45
Limestone utilization, % (based on total slurry)	36	38	64	61
Sulfite oxidation in oxidation tank, %	98	97	97	96
Sulfite oxidation in scrubber inlet slurry, %	86	49	39	29
Gypsum saturation in scrubber inlet liquor, %	120	85	105	105
Gypsum saturation in oxidation tank, %	115	90	115	115
Effective Mg^{++} concentration in scrubber inlet liquor, ppm	4990	5215	5380	4970
Oxidation tank liquor sulfite concentration, ppm	65	105	220	230
Air stoichiometry, atoms O/mole SO_2 absorbed	1.55	1.60	1.60	2.0
Filter cake solids, wt%(2)	83	85	85	84
Onstream hours	205	159	229	246

Notes:

(1) Air discharged downward through 3-inch diameter pipe with an open elbow at center of oxidation tank about 3 inches from tank bottom.
(2) Clarifier and filter in series used for solids dewatering in all runs.
(3) Desired flow rate was 35,000 acfm but problems with the venturi plug lifting mechanism limited the rate to 26,500 acfm.

as expected in runs with MgO. Oxidized slurry solids in all runs had good dewatering properties, averaging about 84 percent solids in the filter cake.

In Runs 823-1A and 824-1A, conducted at 18,000 acfm and 35,000 acfm, respectively, 97 to 98 percent sulfite oxidation was achieved at an air stoichiometry of about 1.6 atoms oxygen/mole SO_2 absorbed. Oxidation was consistently high even though the oxidation tank pH averaged 6.3 in Run 823-1A and at times rose as high as 6.7.

In these runs, 30 gpm of oxidized slurry was recycled from the oxidation tank back to the scrubber hold tank through the oxidation tank overflow. The purpose of this recycle was to suppress the slurry pH rise in the oxidation tank (caused by the dissolution of residual alkali) to obtain good oxidation. However, the opposite occurred. The hold tank pH was depressed, requiring excess limestone feed to maintain a scrubber inlet pH of 5.3. The net result was a limestone utilization of less than 40 percent for these runs. This phenomenon was attributed to the limestone blinding by $CaSO_3$ precipitated in the scrubber slurry loop. Sufficient $CaSO_3$ crystal seeds were not available in the scrubber loop because the slurry had high gypsum content caused by the recycle stream. The blinded limestone (in high excess quantity) eventually dissolved in the oxidation tank resulting in the high pH observed.

Runs 825-1A and 826-1A (at 18,000 acfm and 26,500 acfm, respectively) were conducted without this recycle. In both of these runs, the pH difference between the scrubber hold tank and the oxidation tank averaged only 0.1 and 0.2, with the oxidation tank pH averaging 5.65 or less. Oxidation greater than 95 percent was easily achieved in both runs with air stoichiometric ratios of 1.6

and 2.0, respectively. Time was not available in the test block to determine minimum air stoichiometry. Control of limestone feed was poor in these runs, resulting in relatively low limestone utilization (64 and 61 percent, respectively).

This short series of runs has shown that in systems containing magnesium ion, the slurry bleed stream can be readily oxidized. Furthermore, oxidation of the bleed stream does not interfere with enhancement of SO_2 removal by the magnesium ion as was experienced when oxidation was accomplished within the scrubber loop (see Subsection 6.2.1).

8.3 SUMMARY OF FINDINGS

Findings from bleed stream oxidation tests included the following:

- Bleed stream oxidation is not expected to work with lime or limestone slurries without magnesium oxide addition. Slurry pH rise, caused by the dissolution of residual alkali, prevents solid calcium sulfite from dissolving and oxidizing in the liquid phase. The pH rise also reduces the oxidation rate.
- Bleed stream oxidation of limestone slurry is feasible in the presence of magnesium ion. Magnesium ion tends to buffer the pH rise from dissolving residual alkali in the waste slurry solids, and it tends to promote dissolved sulfite availability, allowing oxidation to take place at a higher pH.
- Average sulfite oxidation of 96 percent or higher was achieved with 1.6 air stoichiometry, 5.4 to 6.3 oxidation tank pH, 18-ft oxidation tank level, and 5000 ppm effective magnesium ion concentration. Oxidation was consistently high even though oxidation tank pH rose as high as 6.7.
- Oxidized slurry in all runs had good dewatering properties, averaging about 84 percent filter cake solids concentration.
- Oxidation of the bleed stream did not interfere with the enhancement of SO_2 removal by the magnesium ion as was experienced when oxidation was accomplished within the scrubber loop.
- In two runs (Run 823-1A and 824-1A), 30 gpm of oxidized slurry was recycled from the oxidation tank back to the scrubber effluent hold

tank in an attempt to reduce the pH difference between the two tanks. However, the opposite occurred. The hold tank pH was depressed, requiring excess limestone feed to maintain a pH of 5.3, resulting in a very poor limestone utilization (less than 40 percent). This phenomenon was attributed to the limestone blinded by $CaSO_3$ precipitated in the scrubber slurry loop. Sufficient $CaSO_3$ crystal seeds were not available because the slurry had high gypsum content caused by the recycle stream. The 30 gpm recycle flow proved to be unnecessary in the succeeding two runs (Run 825-1A and 826-1A). Without the recycle flow, the pH difference between the two tanks averaged only 0.1 and 0.2 pH units with the oxidation tank pH averaging 5.65 or less.

Additional testing has been planned in the future to fully characterize the limestone/MgO bleed stream oxidation system. Better operational control is required to improve the limestone utlization. Higher limestone utilization, however, is not expected to have an adverse effect on the oxidation efficiency because of the reduced amount of residual alkali and the correspondingly less possibility of pH rise in the oxidation tank. The possibility of bleed stream oxidation on a lime/MgO system must also be investigated.

Section 9

TCA LIMESTONE TEST RESULTS WITH LOW FLY ASH LOADING

A series of six limestone runs was made from late November 1976 through early February 1977 using flue gas with low fly ash loading in the TCA system. Two major objectives for this test block were: 1) to compare system performance with high and low fly ash loadings in the flue gas and 2) to investigate scrubber inlet slurry pH and SO_2 removal, with low fly ash loading, as functions of percent solids recirculated, effluent hold tank residence time, the number of hold tanks, and limestone stoichiometric ratio.

9.1 SYSTEM DESCRIPTION

The TCA operated during this test block in a single scrubber loop configuration with either a single effluent hold tank or with three hold tanks in series. Limestone slurry was fed to the first hold tank. Slurry bleed was taken either from the single hold tank or the third of the three hold tanks in series. Dewatering was accomplished by a thickener followed by a centrifuge. All slurry liquor from the dewatering system was returned to the scrubber loop.

9.2 DISCUSSIONS OF TEST RESULTS

Runs 701-2A through 706-2A constituted this test block. The major test conditions common to all were:

TCA gas velocity	12.5 ft/sec
Liquid-to-gas ratio	50 gal/Mcf
Fly ash loading	low (0.04 to 0.20 gram/scf dry)

The results of this test block, along with the major operating conditions, are summarized in Table 9-1. Detailed test results and operating conditions are reported in Appendices H, I, and J.

9.2.1 Effect of Fly Ash

Evaluation of the effect of fly ash on SO_2 removal performance was not possible possible because earlier limestone runs with fly ash were made using a different type of mobile spheres and different liquid and gas rates. However, a limited comparison of the scrubber inlet slurry pH at the same limestone utilization indicated that fly ash tends to depress the pH by 0.3 to 0.4 pH unit. This behavior is consistent with the observation made earlier during lime runs and utilization testing. In those tests, at a controlled scrubber inlet pH of 8, lime utilization for the tests with low fly ash loading averaged about 93 percent, compared with about 88 percent for runs made with fly ash under similar test conditions (Reference 4). This difference was believed to be caused by the acidic fly ash which releases its acidity from absorbed SO_3 under scrubber conditions, even through the fly ash pond liquor at Shawnee is alkaline after a prolonged period of leaching.

9.2.2 Effect of Recirculated Solids

Run 701-2A was the first and the base case run. In addition to the test

Table 9-1

SUMMARY OF TCA LIMESTONE TESTS WITH LOW FLY ASH LOADING

	701-2A	702-2A	703-2A	704-2A	705-2A	706-2A
Gas rate, acfm @ 300°F	30,000	30,000	30,000	30,000	30,000	30,000
Liquor rate, gpm	1200	1200	1200	1200	1200	1200
Percent solids recirculated	8	15	8	8	15	15
Residence time, min.	4.1	4.1	4.1	12	12	12
Number of hold tanks	1	1	1	3	3	1
Stoichiometric ratio (controlled)	1.2	1.2	1.1	1.1	1.1	1.1
Solids dewatering system	Cl & Ce	(1)	Cl & Ce	Cl & Ce	Cl	Cl
Scrubber inlet pH	5.80	5.85	5.65	5.7	5.85	5.55
Stoichiometric ratio	1.21	1.16	1.12	1.10	1.12	1.13
Scrubber inlet SO_2, ppm	2700	3000	2950	2700	2850	2850
Percent SO_2 removal	87	81	74	77	84	81
Inlet percent sulfate saturation @ 50°C	45	20	25	65	60	120
Percent sulfite oxidation	12	7	7	13	11	18
SO_2 make-per-pass, m-mol/l	12.5	13.0	12.0	11.5	12.5	12.0
Scaling	Yes (sulfite)	No	No	No	No	No
Centrifuge cake solids, %	48	58	54	48	--	--

Notes:

(1) Centrifuge only for the first 90 hours and clarifier only thereafter.

(2) Clarifier (Cl) or clarifier followed by centrifuge (Cl & Ce).

conditions previously mentioned, other pertinent test conditions for this run were:

Percent recirculated solids = 8 percent
Stoichiometric ratio = 1.21 moles Ca/mole SO_2 absorbed
Residence time = 4.1 minutes
No. of hold tanks = 1

During Run 701-2A, SO_2 removal averaged 87 percent and inlet slurry pH averaged 5.80 at an average inlet SO_2 concentration of 2700 ppm.

For Run 702-2A all conditions were the same as those in Run 701-2A except the recirculated slurry solids concentration was increased from 8 to 15 percent. SO_2 removal for this run averaged 81 percent and inlet slurry pH averaged 5.85 units at an average inlet SO_2 concentration of 3000 ppm. The improvement expected in SO_2 removal performance was masked by the higher inlet SO_2 concentration during Run 702-2A.

The same effect was investigated at a 12-minute residence time with 3 effluent hold tanks. Run 704-2A was made with 8 percent solids whereas Run 705-2A was made with 15 percent solids. All other conditions were the same. During Run 705-2A, the scrubber inlet liquor pH averaged 5.85, up from an average 5.7 during Run 704-2A. The SO_2 removal averaged 84 percent at an average inlet SO_2 concentration of 2850 ppm, compared with 77 percent SO_2 removal at an average inlet SO_2 concentration of 2700 ppm for Run 704-2A.

Hence, the effect of increased recirculated solids is an improved SO_2 removal performance. The effect is more pronounced at the larger (12 minutes) residence time with 3 tanks in series.

9.2.3 Effect of Limestone Stoichiometric Ratio

Maintaining all other conditions as those in Run 701-2A, the limestone stoichiometric ratio was dropped from 1.2 to 1.1 for Run 703-2A.

The results were an average SO_2 removal of 74 percent and an average inlet pH of 5.65 at an average inlet SO_2 concentration of 2950 ppm. As expected, SO_2 removal performance deteriorated for this run, and the rate of scale deposition on the mist eliminator vanes was significantly less than in Run 701-2A.

9.2.4 Effect of Hold Tank Configuration

Runs 705-2A and 706-2A differed only in the hold tank configuration. Run 7052A was made with three tanks in series; Run 706-2A was made with one tank.

During Run 706-2A, the scrubber inlet pH averaged 5.55, compared with 5.85 for Run 705-2A. SO_2 removal for Run 706-2A averaged 81 percent at an average inlet SO_2 concentration of 2850 ppm, compared with 84 percent SO_2 removal at the same average inlet SO_2 concentration for Run 705-2A.

Thus, the overall effect, as seen in earlier tests (see Section 8, Reference 3), was a slight deterioration in performance in changing from three tanks to one tank.

9.2.5 Gypsum Unsaturated Operation

Runs 701-2A through 705-2A were operated under conditions which resulted in very low gypsum saturation. During these runs the sulfate saturation of the inlet liquor ranged from 20 to 65 percent. The low sulfate saturation was most likely due to the extremely low sulfite oxidation (7 to 13 percent) which may have been the result of operating at relatively high inlet pH (5.65 to 5.85). In addition, Run 701-2A had indications of sulfite precipitation within the scrubber, resulting in reduced liquor sulfite available for oxidation in the effluent hold tank.

9.3 SUMMARY OF FINDINGS

The operating characteristics of limestone scrubbing with high and low fly ash loadings in the flue gas are very similar. The following is a summary of findings and conclusions for this test block:

- At a given limestone stoichiometric ratio, high fly ash loading in the flue gas tends to depress the pH by about 0.3 to 0.4 pH unit.
- At a given limestone stoichiometric ratio, increasing recirculated slurry solids concentration from 8 to 15 percent will increase SO_2 removal efficiency.
- Increasing limestone stoichiometric ratio improves SO_2 removal efficiency but makes it more difficult to keep the mist eliminator clean.
- At a given limestone stoichiometric ratio and hold tank residence time, three hold tanks in series results in higher SO_2 removal efficiency than a single hold tank.

Except for the first conclusion, the other results were also observed for runs with high fly ash loading.

Section 10

TCA LIMESTONE TYPE AND GRIND TEST RESULTS

A limited set of six tests was conducted on the TCA system during the period from March 4 through April 2, 1977 to investigate the effect of limestone type and grind on system performance. System performance was evaluated in terms of SO_2 removal and scrubber inlet slurry pH at a controlled stoichiometric ratio of 1.2 moles Ca/mole SO_2 removed. Limestone type, limestone grind, effluent hold tank (EHT) residence time, and effluent hold tank configuration were varied.

10.1 TEST PROGRAM

The independent variables evaluated in this test series were:

- Limestone grind -- fine (96 percent less than 325 mesh) versus coarse (65 to 69 percent less than 325 mesh)
- Limestone type -- Fredonia White versus Longview, Alabama
- Effluent hold tank residence time -- 4.1 minutes versus 12 minutes
- Effluent hold tank configuration -- single tank versus three tanks in series

To allow a comparison among the independent variables within the time available, the test series was arranged according to Figure 10-1. Table 10-1 shows the

Figure 10-1

Test Program Arrangement

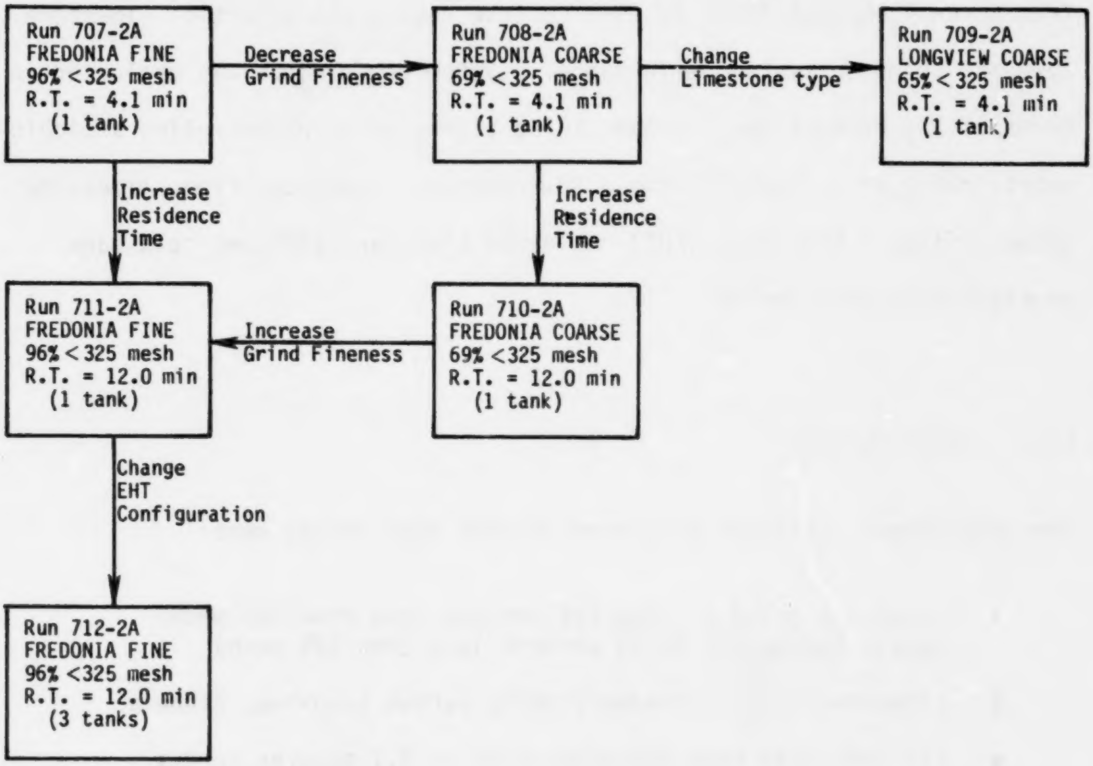

Run 707-2A
FREDONIA FINE
96% <325 mesh
R.T. = 4.1 min
(1 tank)
Decrease
Grind Fineness
Run 708-2A
FREDONIA COARSE
69% <325 mesh
R.T. = 4.1 min
(1 tank)
Change
Limestone type
Run 709-2A
LONGVIEW COARSE
65% < 325 mesh
R.T. = 4.1 min
(1 tank)
Increase
Residence
Time
Increase
Residence
Time
Run 711-2A
FREDONIA FINE
96% < 325 mesh
R.T. = 12.0 min
(1 tank)
Increase
Grind Fineness
Run 710-2A
FREDONIA COARSE
69% <325 mesh
R.T. = 12.0 min
(1 tank)
Change
EHT
Configuration
Run 712-2A
FREDONIA FINE
96% <325 mesh
R.T. = 12.0 min
(3 tanks)

Table 10-1

LIMESTONE ANALYSIS FOR RUNS 707-2A TO 712-2A

Bahco Analysis	Fredonia Fine	Fredonia Coarse	Longview Coarse
Micron Size	wt% Less Than	wt% Less Than	wt% Less Than
3	39.5	21.1	16.1
6	57.9	31.4	26.8
9	67.8	38.4	34.4
12	73.8	43.6	40.0
16.5	80.0	49.4	47.0
22	84.7	54.8	48.0
27	87.6	58.6	57.4
30	88.9	60.4	59.2
Screen Analysis			
Mesh Size	wt% Less Than	wt% Less Than	wt% Less Than
400	93.1	64.6	61.7
325	95.9	69.1	64.8
200	99.3	80.8	74.6
100	99.4	81.0	74.8
50	100.0	99.9	99.3
30	100.0	100.0	100.0
Number of Samples	2	6	2

Chemical Analysis			
CaO	54.14 wt%	53.18 wt%	54.23 wt%
MgO	0.48	0.74	0.66
CO_2	39.56	39.54	39.99
Acid insolubles	2.18	2.27	1.27
Number of Samples	6	11	4

results of size and chemical analyses of the limestone grinds. Both Bahco and screening procedures were used for size analyses.

10.2 RESULTS

Pertinent results and the major test conditions are presented in Table 10-2. Detailed test results and operating conditions are reported in Appendices H, I, and J. Discussion of the effect of each variable tested is presented below.

10.2.1 Effect of Grind

The effect of grind with Fredonia White limestone was investigated at two effluent hold tank residence times, 4.1 and 12 minutes. Runs 707-2A and 708-2A were conducted at 4.1 minutes' residence time. As indicated in Table 10-2, use of the more finely ground Fredonia limestone resulted in higher SO_2 removal by 23 percentage points and higher inlet slurry pH by 0.4 pH unit.

Similar tests, Runs 710-2A and 711-2A, at 12 minutes residence time resulted in higher SO_2 removal by 10 percentage points and higher inlet slurry pH by 0.25 pH unit when using the finer ground limestone. Thus, it appears that the benefits of fine grinding are greater at the lower residence time than at the higher residence time. This behavior is consistent with the fact that SO_2 removal in wet-limestone scrubbing systems is profoundly influenced by the rate and the amount of time available for limestone dissolution.

Table 10-2

SUMMARY OF TCA LIMESTONE TYPE AND GRIND TESTS
(with fly ash, no MgO addition)

Major Test Conditions[1]	707-2A	708-2A	709-2A	710-2A	711-2A	712-2A
Limestone type	Fredonia	Fredonia	Longview	Fredonia	Fredonia	Fredonia
Average grind, wt% <325 mesh	96	69	65	69	96	96
Gas rate, acfm @ 300°F	30,000	30,000	30,000	30,000	30,000	30,000
Liquor rate, gpm	1200	1200	1200	1200	1200	1200
Percent solids recirculated	15	15	15	15	15	15
Effluent residence time, min.	4.1	4.1	4.1	12	12	12 (3 tanks)
Limestone stoichiometric ratio (controlled)	1.2	1.2	1.2	1.2	1.2	1.2
Selected Results						
Scrubber inlet pH	5.6	5.2	5.3	5.4	5.65	5.85
Stoichiometric ratio	1.23	1.15	1.18	1.21	1.25	1.21
Percent SO_2 removal	72	49	55	54	64	69
Inlet SO_2 concentration, ppm	3100	3100	3350	3400	3250	3050
SO_2 make-per-pass, m-mol/liter	11.5	8.0	9.5	9.5	11.0	11.5
Inlet liquor % gypsum saturation @ 50°C	100	115	110	110	80	60
Percent sulfite oxidation	17	14	20	16	15	18
Onstream hours	113	128	56(2)	162	93	117

Notes:

(1) Clarifier only used for solids dewatering in all runs.
(2) Run 709-2A was terminated prematurely due to severe limestone feed line plugging problems.

10.2.2 Effect of Limestone Type

To compare the effect of limestone type, limestone from Longview, Alabama, was tested in Run 709-2A. This limestone was ground to a nominal 70 percent less than 325 mesh.

Comparison of Runs 708-2A and 709-2A indicates a 6 percent increase in SO_2 removal and 0.1 unit improvement in inlet slurry pH in going from the Fredonia coarse to the Longview coarse limestone. However, even though SO_2 removal improved with the Longview limestone, severe limestone feed-line plugging problems were experienced. This required premature termination of Run 709-2A. The plugging was attributed to coarsely ground insolubles in the Longview limestone.

10.2.3 Effect of Effluent Hold Tank Residence Time

Results from Runs 707-2A, 708-2A, 710-2A and 711-2A were also evaluated in terms of the effect of effluent hold tank residence time for a given limestone.

Runs 707-2A and 711-2A were compared to evaluate the effect of an increase from 4.1 to 12.0 minutes in effluent hold tank residence time for the Fredonia fine limestone. SO_2 removal dropped by 8 percentage points at the higher residence time and the inlet slurry pH was higher by 0.05 pH unit. This behavior, which was contrary to expectations, may have been the result of inadequate control of variables other than residence time.

For the coarse Fredonia case, Runs 708-2A and 710-2A were compared. It was found that increasing the residence time from 4.1 to 12.0 minutes improved SO_2 removal by 5 percentage points and the inlet slurry pH by 0.2 pH unit. This behavior was in line with expectations.

The relative merits of an increased residence time for the two limestone grind classes could not be quantified from these runs because of the anomalous behavior during the tests of finely ground limestone.

10.2.4 Effect of Effluent Hold Tank Configuration

As indicated by comparison of Runs 711-2A and 712-2A, three tanks in series improved the SO_2 removal by 5 percentage points and the inlet slurry pH by 0.2 pH unit.

10.3 SUMMARY OF FINDINGS

For the variables evaluated in this limited test series, the fineness of grind had the greatest effect on improving SO_2 removal. Effluent hold tank residence time, limestone type, and effluent hold tank configuration all had lesser effects.

To achieve a desired degree of SO_2 removal, consideration must be given to the cost trade-off between the use of coarse-ground limestone and fine-ground limestone. Use of coarse limestone requires higher limestone stoichiometry, resulting in more waste sludge to be disposed of. Use of fine limestone, on the other hand, requires higher capital and operating costs for the ballmills, but lower limestone stoichiometry with less waste sludge generated.

A more extensive limestone type and grind testing program is currently scheduled in the Shawnee Advanced Program.

Section 11

TCA AUTOMATIC LIMESTONE FEED CONTROL TESTING

A four-week period in the TCA test program, beginning after the April-June 1977 Boiler No. 10 outage, was reserved for the testing of an automatic limestone feed control system. However, electronic stability problems with the "track-and-hold" module developed during Run 713-2A, and the test block was deferred to a later date until these problems could be solved. A later attempt during Run 714-2A was somewhat more successful. Summarized results are included in Appendices H and I.

11.1 TEST PROGRAM OBJECTIVES

The objectives of the study were to determine the feasibility of automatic limestone feed control in a limestone wet-scrubbing system and to observe other benefits that may be gained. Benefits include:

- Minimizing the limestone usage to meet the SO_2 emission standard
- Reducing the number of manual operation and operator errors
- Reducing the scrubber operating costs
- Improving reliability by reducing the potential for plugging with soft mud-type solids caused by excessive limestone stoichiometry

11.2 BASIS FOR THE LIMESTONE FEED CONTROL SCHEME

In a lime wet-scrubbing system, the lime addition rate can be controlled by pH variations in the scrubber feed slurry. This type of control is not feasible for the limestone system because the slurry pH is well buffered in the normal operating range of 5.6 to 6.0. In view of the above limitation, the limestone feed control scheme proposed for testing at Shawnee was based on the material balance concept, i.e., maintaining a desired stoichiometric limestone feed in relation to the amount of SO_2 entering or absorbed in the scrubber. The basic control scheme is represented by the following equation:

Limestone (60 percent slurry) addition rate, gpm = G x (SO2I-Kout) x KSR

where G = flue gas flow rate, acfm @ 300°F

SO2I = inlet SO_2 concentration measured by Du Pont analyzer (wet), ppm

Kout = a manually adjustable constant related to desired outlet SO_2 concentration, ppm

KSR = a manually adjustable constant proportional to the stoichiometric ratio
= (unit conversion factor) x (stoichiometric ratio)
= 2.34×10^{-8} x (stoichiometric ratio)

The factor G(SO2I-Kout) represents the amount of SO_2 absorbed per unit time. Thus, at a set value of KSR which is proportional to the desired stoichiometric ratio, the limestone addition rate is automatically adjusted to maintain the desired stoichiometry.

In practice, inlet SO_2 concentration, SO2I, and flue gas flow rate, G, may vary within a wide range depending on the sulfur content in the coal and on the boiler load. Therefore, the proposed control scheme included overrides which can be activated when the following situations arise:

- If the outlet SO_2 concentration exceeds a set maximum, the limestone addition rate will be stepped up to a preset maximum.
- If the outlet SO_2 concentration drops below a set minimum, the limestone addition rate will be stepped down to a preset minimum.

The former provision minimizes the infringement of the SO_2 emission standard; the latter allows limestone savings by avoiding unnecessary SO_2 removal.

11.3 EXPERIENCE

Experience with this first-generation design, though quite limited, has indicated several areas for improvement. One such area involves setting the limestone flow rate when override conditions (violations of EPA NSPS or excess removal) are encountered. At present, the system merely reverts to either a minimum or maximum limestone flow rate setting depending on the override condition encountered, regardless of the deviation between the SO_2 outlet set-point and the actual SO_2 outlet concentration. This shortcoming of the present design generally results in underfeeding and overfeeding of limestone, with resultant loss in performance and sometimes system scaling. The modification proposed would add a proportioning device to regulate the limestone flow rate (at the override conditions) in proportion to the difference between outlet SO_2 set-point and prevailing SO_2 outlet concentration. Other modifications, though somewhat complex, include stoichiometry override and/or pH override.

11.4 ALTERNATIVES

The Shawnee control scheme presented above can be altered to test other schemes. Tests of the following schemes are planned:

- Limestone addition rate = G x (SO2I-Kout)KSR, at constant G and subject to overrides
- Limestone addition rate = G x (SO2I-Kout)KSR, at constant G and without overrides
- Limestone addition rate = G x (SO2I-Kout)KSR, at variable G (following boiler load) and subject to overrides
- Limestone addition rate = G x (SO2I-Kout)KSR, at variable G and without overrides
- Limestone addition rate = G x SO2I x KSR, at variable G and subject to overrides
- Limestone addition rate = G x SO2I x KSR, at variable G and without overrides (this scheme is used by Research-Cottrell at Rickenbacker Air Force Base)

It may not be possible to make all of these tests in a specific time period allowed. However, if the tests are successful, the testing may be conducted concurrently with other TCA test blocks. The successful operation of the automatic limestone feed control system will be gauged according to the achievement of the following goals:

- To attain reliable (nonscaling) operation of the scrubber and the mist eliminator
- To minimize (1) the number of times the control overrides occur and (2) the number of instances of operator adjustments
- To minimize required limestone consumption while meeting the emission standard

Section 12

TCA ONE-SCRUBBER-LOOP FORCED-OXIDATION LIMESTONE TESTS WITH AIR EDUCTOR

Beginning in late June 1977, the TCA system was operated as a single scrubber stage with forced oxidation in the scrubber slurry loop. As an alternative to the type of air sparger used in the venturi/spray tower system, an air eductor was used to bring about air/slurry contact. Tests were conducted with limestone slurry and with high fly ash loadings. Because sulfite is the major SO_2 scrubbing species in a lime scrubber, no one-scrubber-loop forced-oxidation tests were made with lime slurry. Forced oxidation within the scrubber loop converts the sulfite to sulfate in the slurry liquor, resulting in poor SO_2 removal. With limestone slurry, one-scrubber-loop forced oxidation was successfully accomplished with good SO_2 removal.

The one-scrubber-loop configuration is of prime interest commercially because most commercial installations, both operating and planned, are of this type. Modification of these installations for forced oxidation would require as a minimum a compressor (or blower) plus an air sparger in the scrubber hold tank (Section 15), or an eductor and a pump, as will be described later.

A total of 15 runs were made using limestone slurry with high fly ash loadings. These included 11 runs made from June 24 through August 29, 1977, with the air eductor mounted in a vertical position over the oxidation tank, and 4 runs from September 9 through October 4, 1977, with the eductor in a horizontal position beside the oxidation tank. Each test run normally lasted 5 to 6 days.

Table 12-1 summarizes the major test conditions and important test results for the 15 runs. Additional detailed information can be found in Appendices B through D, and H through J.

12.1 SYSTEM DESCRIPTION

An air eductor, Penberthy-Houdaille Model ELL-10 Special, was used to provide air/slurry contact. The high velocity of the slurry pumped through the eductor nozzle aspirates air into the liquid stream. The high shear developed in the throat of the eductor breaks air into minute bubbles which are ejected into the oxidation tank, aerating the slurry in the tank.

The main feature of an eductor is its ability to create smaller air bubbles than can be obtained with an air sparger, and hence a higher mass transfer coefficient. However, an air eductor consumes more energy than an air sparger and is more prone to severe erosion in high-velocity slurry service.

The eductor used was capable of educting 600 scfm of air from the atmosphere at zero back pressure with a slurry flow rate of 1600 gpm. The eductor nozzle and the whirler within the nozzle were made of stellite, and the body was made of neoprene-lined carbon steel.

Two flow configurations were used in the one-scrubber-loop forced oxidation tests. In the one-tank configuration (Figure 12-1) slurry was recirculated from the TCA effluent hold tank (oxidation tank) through the eductor and back

Table 12-1

SUMMARY OF ONE-SCRUBBER-LOOP FORCED-OXIDATION LIMESTONE TESTS WITH AIR EDUCTOR ON THE TCA SYSTEM

Major Test Conditions	801-2A	801-2B	802-2A	803-2A	804-2A	805-2A	806-2A
Fly ash loading	High	High	High	High	High	High	High
Gas rate, acfm @ 300°F	30,000	30,000	30,000	30,000	30,000	30,000	30,000
Slurry flow rate to TCA, gpm	1200	1200	1200	1200	1200	1200	1200
Slurry flow rate to eductor, gpm	1600	1600	1600	1600	1600	1600	1200
Percent solids recirculated	15	15	15	15	15	15	15
EHT (oxidation tank) residence time, min.(1)	12	15.7	23.5	23.5	23.5	23.5	23.5
Downcomer (low pH) tank residence time, min.(1)	-	-	-	-	-	-	-
EHT level, ft	6.1	8.0	12	12	12	12	12
Eductor mounting position in EHT	Ver.	Ver.	Ver.	Ver.	Ver.	Ver.	Ver.
Eductor discharge point, ft from EHT bottom	6(4)	6(4)	10	10	10	10	10
Limestone stoichiometric ratio controlled at	1.2	1.2	1.2	-	-	-	-
TCA inlet pH controlled at	-	-	-	5.0	5.0	5.3	5.3
EHT (oxidation tank) agitator speed, rpm	45	45	45	45	68	68	68
Limestone addition point(2)	EHT	EHT	EHT	EHT	EHT	TCA	TCA
Air flow rate to eductor, scfm	~600	530	485	465	410	470	290
Selected Results							
Percent SO_2 removal	70	70	76	62	62	72	70
Inlet SO_2 concentration, ppm	2750	2750	2900	2950	3000	3050	3000
Percent sulfite oxidation	53	63	56	91	93	93	58
Air stoichiometry, atoms O/mole SO_2 absorbed	6.4	5.6	4.5	5.2	4.5	4.4	2.8
TCA inlet pH	5.8	5.8	5.75	5.05	5.0	5.35	5.35
Eductor inlet pH	5.8	5.8	5.75	5.05	5.0	5.25	5.3
Percent limestone utilization	80	80	82	90	93	84	91
Gypsum saturation in TCA inlet liquor, %	105	105	100	105	105	105	110
Onstream hours	102	47	142	165	166	140	115

Note: Footnotes for this table are listed in Table 12-1 (continued).

Table 12-1 (continued)

SUMMARY OF ONE-SCRUBBER-LOOP FORCED-OXIDATION LIMESTONE TESTS WITH AIR EDUCTOR ON THE TCA SYSTEM

Major Test Conditions	807-2A	808-2A	809-2A(3)	810-2A(3)	811-2A	812-2A	813-2A	814-2A
Fly ash loading	High	High	High	High	High	High	High	High
Gas rate, acfm @ 300^{o}F	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000
Slurry flow rate to TCA, gpm	1200	1200	1200	1200	1200	1200	1200	1200
Slurry flow rate to eductor, gpm	1600	1600	1600	1600	1600	1600	1600	1200
Percent solids recirculated	15	15	15	15	15	15	15	15
EHT (oxidation tank) residence time, min.(1)	23.5	23.5	15.7	15.7	23.5	15.7	23.5	15.7
Downcomer (low pH) tank residence time, min.(1)	2.9	2.9	1.9	1.9	2.9	1.9	-	-
EHT level, ft	12	12	8	8	12	8	12	8
Eductor mounting position in EHT	Ver.	Ver.	Ver.	Ver.	Hor.	Hor.	Hor.	Hor.
Eductor discharge point, ft from EHT bottom	10	10	6(4)	6(4)	0.8	0.8	0.8	0.8
Limestone stoichiometric ratio controlled at	-	1.3	1.3	-	1.3	1.3	-	-
TCA inlet pH controlled at	5.4	-	-	5.4	-	-	5.3	5.3
EHT (oxidation tank) agitator speed, rpm	68	68	68	68	68	68	68	68
Limestone addition point(2)	EHT	EHT	EHT	EHT	EHT	EHT	TCA	TCA
Air flow rate to eductor, scfm	475	200(5)	300(5)	300(5)	270	350	310	145
Selected Results								
Percent SO_2 removal	83	71	77	84	87	81	80	74
Inlet SO_2 concentration, ppm	2700	2900	3200	2900	2800	3000	2850	2550
Percent sulfite oxidation	96	93	96	98	96	93	95	61
Air stoichiometry, atoms O/mole SO_2 absorbed	4.3	2.0	2.5	2.5	2.3	2.9	2.8	1.6
TCA inlet pH	5.45	5.1	5.2	5.5	5.85	5.5	5.35	5.35
Eductor inlet pH	5.1	4.95	5.0	5.15	5.45	5.3	5.15	5.3
Percent limestone utilization	82	63	63	77	60	56	90	85
Gypsum saturation in TCA inlet liquor, %	100	125	115	110	100	100	90	115
Onstream hours	185	162	149	130	164	141	130	119

Notes:

(1) Residence times are based on slurry flow rate to TCA.
(2) EHT (effluent hold tank) or TCA (pump suction on the TCA inlet slurry line).
(3) Filter in series with clarifier was used during Runs 809-2A and 810-2A. Filter cake solids contents were 85 and 88%, respectively.
(4) At discharge of 4 ft long by 10-inch diameter pipe attached beneath the eductor.
(5) Air flow controlled by a sliding plate in the air intake line to eductor.

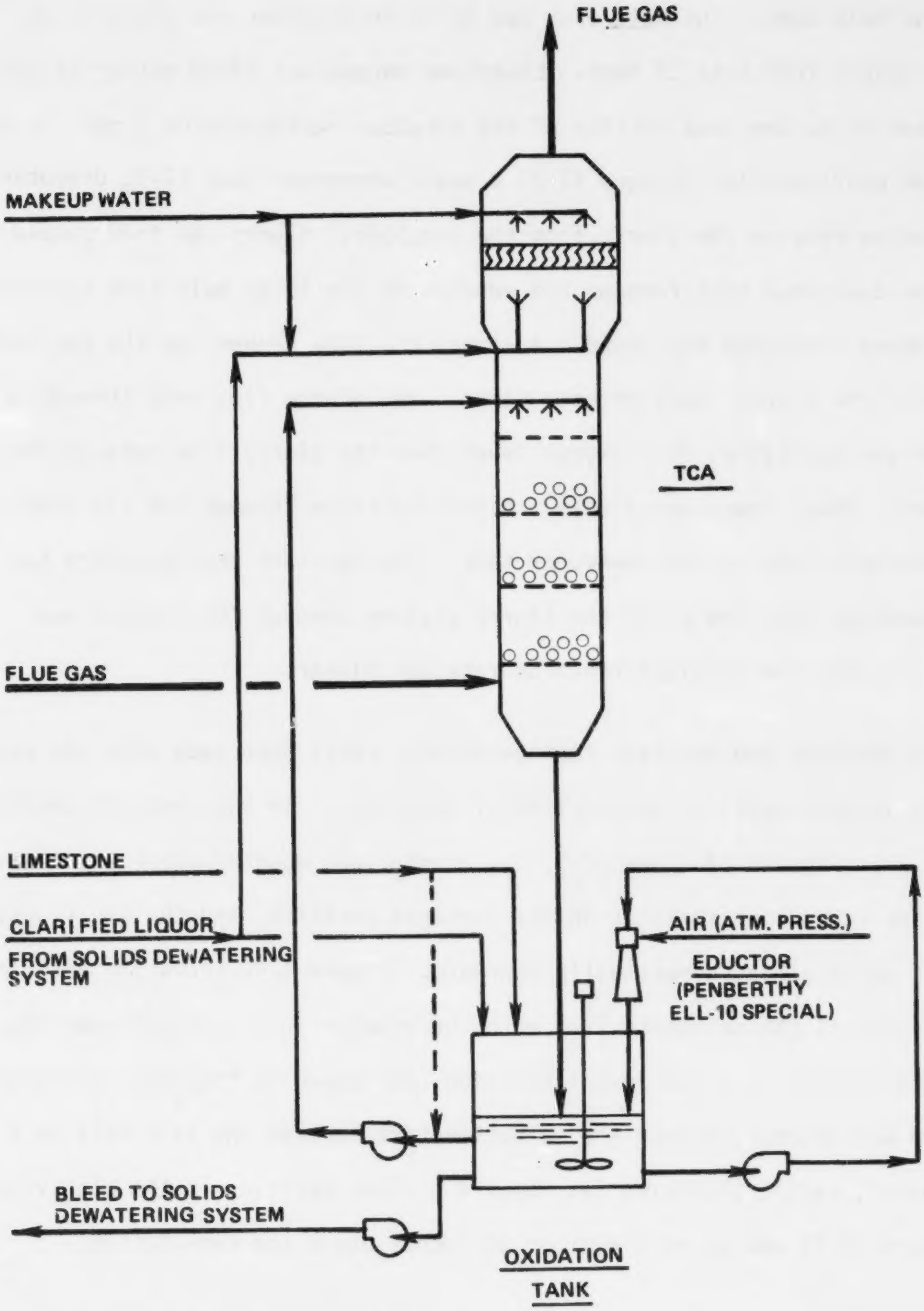

FLUE GAS
MAKEUP WATER
TCA
FLUE GAS
LIMESTONE
CLARIFIED LIQUOR
FROM SOLIDS DEWATERING SYSTEM
AIR (ATM. PRESS.)
EDUCTOR
(PENBERTHY ELL-10 SPECIAL)
BLEED TO SOLIDS DEWATERING SYSTEM
OXIDATION TANK

Figure 12-1. Flow Diagram for One-Scrubber-Loop Forced Oxidation with Air Eductor in the TCA System Using One Tank

into the hold tank. The hold tank was 20 ft in diameter and operated at slurry levels from 6 to 12 feet. Limestone makeup was added either to the hold tank or to the pump suction of the scrubber recirculation line. In the two-tank configuration (Figure 12-2) a small downcomer tank (7-ft diameter) was used to receive the slurry from the scrubber. Slurry was then pumped from the downcomer tank through the eductor to the large hold tank (oxidation tank) where limestone was added. A slurry tie line connecting the two tanks equalized the slurry level in both tanks. The slurry flow rate through the eductor was maintained at a higher level than the slurry flow rate to the scrubber. Thus, there was always a slurry backflow through the tie line from the hold tank to the downcomer tank. The two-tank configuration had the advantage that the pH of the slurry passing through the eductor was lower and thus the chemical reaction rate was higher.

In both one-tank and two-tank configurations, tests were made with the eductor mounted in both vertical and horizontal positions. In the vertical position, as shown in Figures 12-1 and 12-2, the eductor was mounted above the effluent hold tank (oxidation tank) in an off-centered position, and the air/slurry mixture was discharged vertically downward. Figure 12-3 shows the detailed arrangement of the oxidation tank with the eductor in a vertical position. With the eductor in a horizontal position (not shown in figures), air/slurry mixture was discharged into the oxidation tank through the tank wall in a horizontal, radial direction (at about 4 o'clock position in the plan view of Figure 12-3) and at an elevation 10 inches above the tank bottom.

Normally, slurry was bled from the oxidation tank to a clarifier for dewatering. The clarifier operated with an underflow solids concentration of about 35 to 45 percent. In two runs (Runs 809-2A and 810-2A), the clarifier was followed

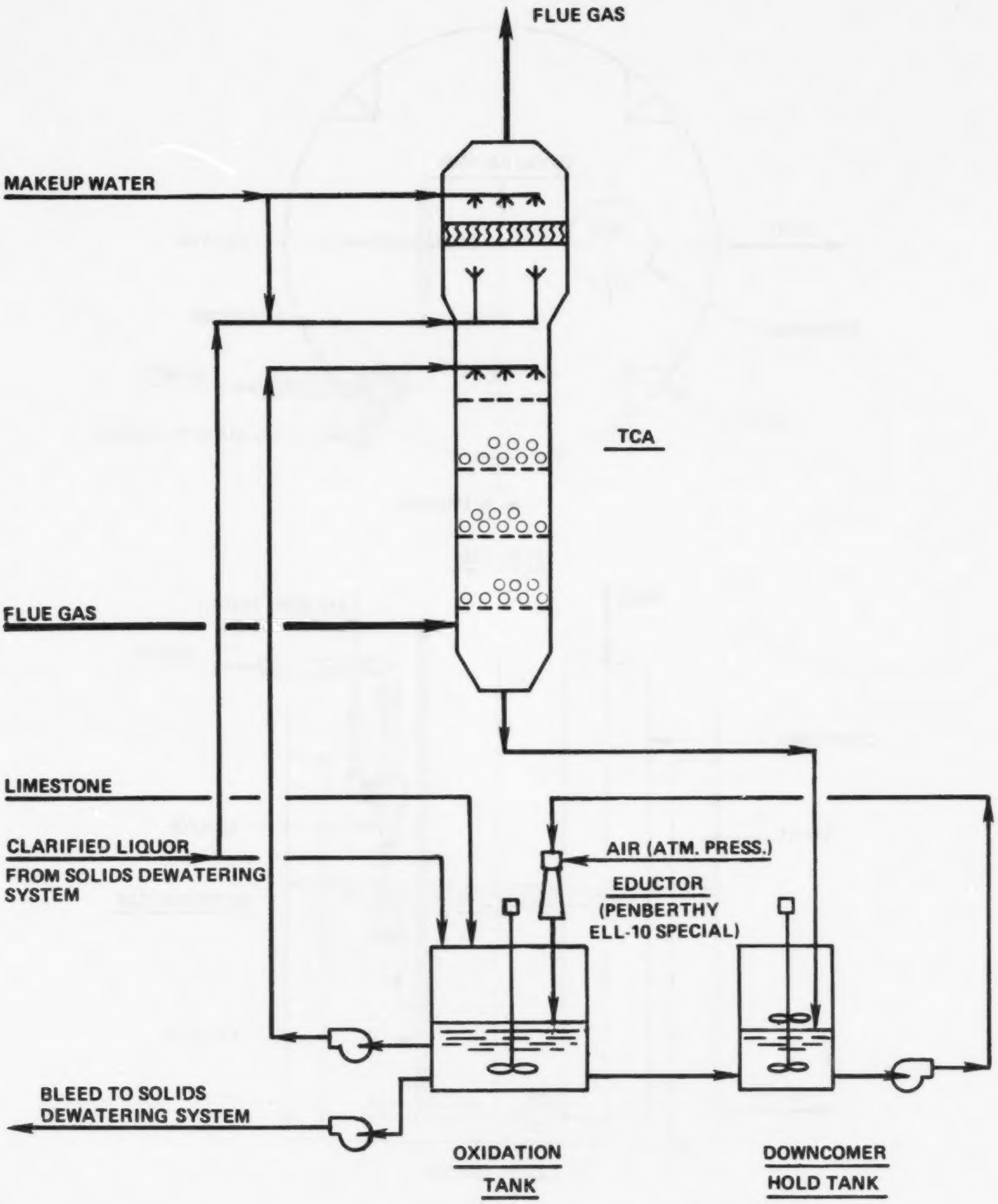
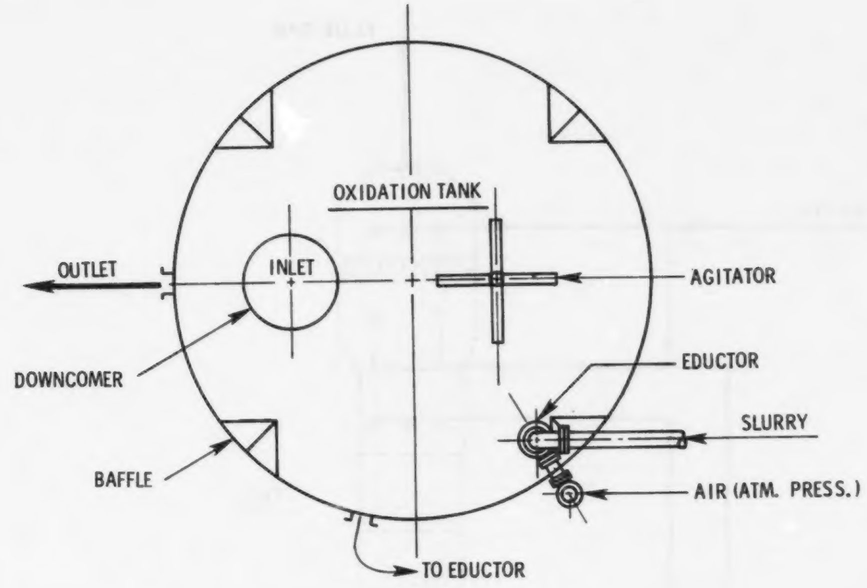
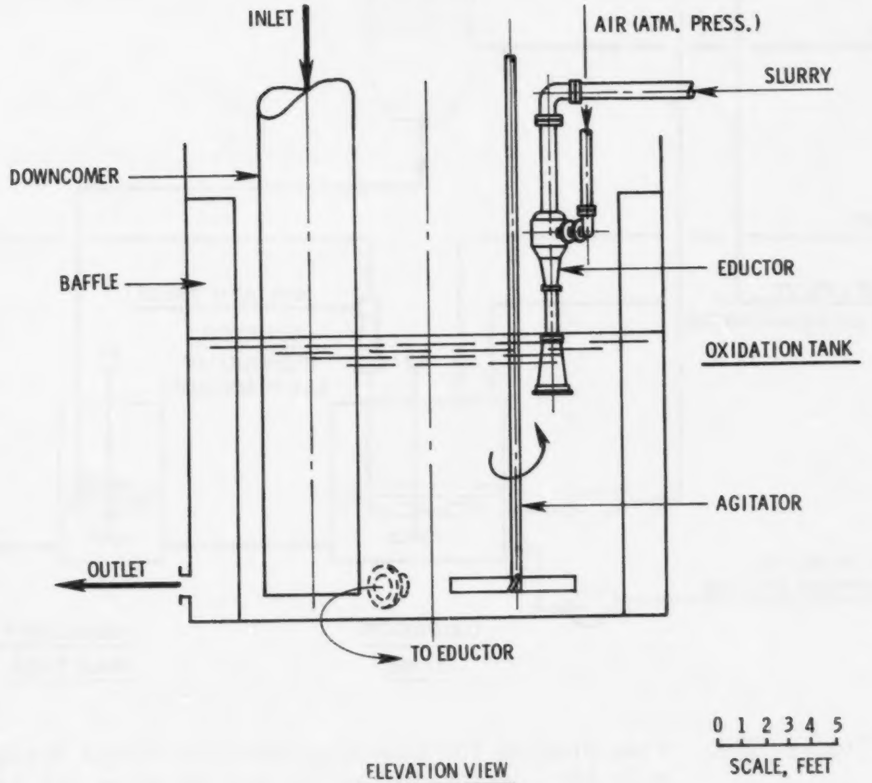

FLUE GAS
MAKEUP WATER
TCA
FLUE GAS
LIMESTONE
CLARIFIED LIQUOR
FROM SOLIDS DEWATERING SYSTEM
AIR (ATM. PRESS.)
EDUCTOR
(PENBERTHY ELL-10 SPECIAL)
BLEED TO SOLIDS DEWATERING SYSTEM
OXIDATION TANK
DOWNCOMER HOLD TANK

Figure 12-2. Flow Diagram for One-Scrubber-Loop Forced Oxidation with Air Eductor in the TCA System Using Two Tanks


OXIDATION TANK
OUTLET
INLET
AGITATOR
EDUCTOR
DOWNCOMER
SLURRY
BAFFLE
AIR (ATM. PRESS.)
TO EDUCTOR

PLAN VIEW


INLET
AIR (ATM. PRESS.)
SLURRY
DOWNCOMER
BAFFLE
EDUCTOR
OXIDATION TANK
AGITATOR
OUTLET
TO EDUCTOR
0 1 2 3 4 5
SCALE, FEET

ELEVATION VIEW

Figure 12-3. Arrangment of the TCA Oxidation Tank with Air Eductor in Vertical Position

by a rotary drum vacuum filter.

12.2 DISCUSSION OF TEST RUN RESULTS

In a one-scrubber-loop forced-oxidation system using limestone slurry, a compromise must be made in the scrubber liquor pH between a higher pH desired for good SO_2 removal and a lower pH required for good sulfite oxidation. Although the optimum oxidation reaction rate occurs at about 4.5 pH (Reference 3), it has been found that the oxidation rate is adequately fast up to a pH of about 6. Thus, the oxidation pH range is compatible with the limestone SO_2 scrubbing pH range of 5 to 6.

12.2.1 Effect of Tank Level in the Initial Runs

Run 801-2A was made with a one-tank configuration and a vertical eductor position (Figure 12-1). With 12 minutes residence time in the effluent hold tank normally used in the past operation without forced oxidation, the slurry level in the 20-ft diameter tank was only 6.1 feet. This was an awkward height-to-diameter ratio for forced oxidation. Good air/slurry contact was difficult to maintain, and the air bubble residence time was short in the shallow tank. Average sulfite oxidation was only 53 percent, with an air stoichiometric ratio of 6.4 atoms oxygen/mole SO_2 absorbed. Air/slurry mixture from the eductor discharged at the slurry surface in the tank through a 4-ft long by 10-inch diameter pipe attached beneath the eductor.

In Run 801-2B, sulfite oxidation was increased to 63 percent by raising the tank level to 8 feet and discharging the eductor 2 feet below the slurry surface. The 2-ft back pressure on the eductor discharge reduced the educted air rate from 600 to 530 scfm, with a corresponding decrease in the air stoichiometry from 6.4 to 5.6.

The oxidation tank level was further raised to 12 ft in Run 802-2A. The 4-ft long spool piece on the eductor discharge was removed, and the eductor was still discharging at 2 feet below the slurry surface. Sulfite oxidation was still poor at 56 percent.

These initial runs were all made at a controlled limestone stoichiometry of 1.2, which corresponded to an oxidation tank pH of 5.8.

12.2.2 Effect of Low pH

In the next two runs (Runs 803-2A and 804-2A), still with a one-tank configuration and a vertical eductor position, better than 90 percent sulfite oxidation was achieved by dropping the oxidation tank pH (TCA inlet pH) to 5.0. These were the first successful one-scrubber-loop forced-oxidation runs in the TCA system at the Shawnee Test Facility. As expected with the low pH, the SO_2 removal was only 62 percent for these runs at 3000 ppm inlet SO_2 concentrations.

Assuming that air/slurry contact time was limited by the poor TCA hold tank configuration, the lower pH must have increased the reaction rate sufficiently for near complete oxidation to take place. At the IERL/RTP pilot plant, where the hold tank had a height-to-diameter ratio approaching one and the mixing was probably more uniform, no limiting effect of pH on oxidation was observed up to about pH 6.0 (Reference 6).

Run 804-2A differed from Run 803-2A by an increase in agitator speed from 45 rpm to the maximum obtainable of 68 rpm. The effect was to increase the average oxidation slightly (from 91 to 93 percent) and to reduce time-dependent fluctuations. Subsequent runs were all made at 68 rpm agitator speed.

12.2.3 SO_2 Removal Improvement

To improve SO_2 removal and still maintain sufficiently low pH in the oxidation tank for good oxidation, the limestone addition point was moved from the effluent hold tank to the pump suction on the scrubber inlet feed line, and the scrubber inlet pH was increased to 5.3 (Run 805-2A). The net result was an increase in SO_2 removal to 72 percent (at 3050 ppm inlet concentration) with a continuation of 93 percent sulfite oxidation. Addition of the limestone to the scrubber feed line allowed the air/slurry contact to take place at the lowest pH in the scrubber system.

This run was the most successful in the series of limestone runs with a single hold tank and a vertical eductor position. The slurry circulation rate through the eductor was 1600 gpm which gave an air rate of 470 scfm, corresponding to an air stoichiometry of 4.4 atoms oxygen/mole SO_2 absorbed.

12.2.4 Effect of Decreased Slurry Rate to the Eductor

In Run 806-2A, the eductor feed rate was reduced to 1200 gpm, with a corresponding reduction in educted air to 290 scfm. Sulfite oxidation dropped to only 58 percent, indicating poor mixing in the oversize effluent hold tank with the reduced eductor discharge flow. The air rate was adequate, as indicated by good oxidation in later runs at a 1600 gpm eductor feed rate and air rates as low as 200 scfm.

12.2.5 Effect of TCA Inlet pH in a Two-Tank Configuration

Runs 807-2A through 810-2A were made with a two-tank configuration and with vertical eductor position (Figure 12-2). With the two-tank mode of operation, fresh limestone was added to the effluent hold tank (oxidation tank), and the eductor inlet pH was maintained at a lower level than the TCA inlet pH (oxidation tank pH). The TCA inlet pH was varied from 5.1 to 5.5 while the eductor inlet pH changed only from 4.95 to 5.15. No systematic effect of pH on sulfite oxidation was observed, but SO_2 removal increased from 71 to 84 percent as the pH was increased.

12.2.6 Effect of Air Rate

The air rate to the eductor was dropped from 475 scfm in Run 807-2A to 200 scfm in Run 808-2A with only a 3 percent reduction in sulfite oxidation (96 percent oxidation reduced to 93 percent). The air rate was controlled at a constant eductor slurry rate of 1600 gpm by restricting the eductor air inlet.

The 200 scfm air rate, corresponding to an air stoichiometry of 2.0 atoms oxygen/mole SO_2 absorbed, was the lowest air rate in the single-loop oxidation series with eductor in which better than 90 percent oxidation was achieved.

12.2.7 Effect of Slurry Tank Level

Of the four runs with a two-tank configuration and a vertical eductor mounting (Runs 807-2A through 810-2A), two were made at a 12-ft oxidation tank level

(23.5 minutes' residence time) and two were at an 8-ft tank level (15.7 minutes' residence time). Sulfite oxidation occurred equally as well at the low tank level (96 and 98 percent) as at the high level (96 and 93 percent). These runs were made over an eductor inlet pH range of 4.95 to 5.15.

12.2.8 Effect of Eductor Mounting Position

Runs 811-2A through 814-2A were made with the eductor mounted in a horizontal position as previously described in Subsection 12.1. In these tests, the eductor discharged against a back pressure close to the liquid head in the oxidation tank.

Runs 811-2A, 812-2A, and 813-2A were conducted under similar conditions as Runs 808-2A, 809-2A, and 805-2A, respectively, except for the difference in the eductor position. No major trend in sulfite oxidation was observed in these runs with a change in eductor position. Percent sulfite oxidations in both cases were in the mid 90's.

In Run 814-2A, the slurry flow to the eductor was reduced to 1200 gpm to observe the effect on sulfite oxidation. The oxidation tank level was also reduced from 12 to 8 ft to obtain a reasonable air flow rate. Actual educted air flow rate was only 145 scfm with the eductor discharging against 7.2 ft of slurry head in the oxidation tank. Sulfite oxidation dropped to only 61 percent, apparently because of both poor mixing (see Subsection 12.2.4) and insufficient air.

12.3 GENERAL OPERATING CHARACTERISTICS OF THE ONE-SCRUBBER-LOOP SYSTEM WITH FORCED OXIDATION USING AN AIR EDUCTOR

12.3.1 Water Balance

In the TCA system, forced oxidation did not significantly change the water balance. In a majority of runs only a clarifier was used for dewatering, and the underflow waste solids concentration was run at 35 to 45 percent, the same as without forced oxidation.

During Runs 809-2A and 810-2A, however, the rotary drum vacuum filter was used in series with the clarifier, and the oxidized filter cake averaged over 85 percent solids concentration. During these runs, the water balance was tighter than normal when clarifier only was used.

12.3.2 Enhancement of SO_2 Removal

SO_2 removal during the one-scrubber-loop forced-oxidation tests has tended to be a few percentage points higher than predicted by the SO_2 removal model fitted to previous Shawnee TCA limestone runs without forced oxidation (Reference 4). The reason for this removal enhancement has not yet been determined. However, one speculation is the limestone dissolution rate has been increased because of the reduction of carbonate in the liquor by air stripping of CO_2 and the reduction of bisulfite by oxidation. Increased agitation in the effluent hold tank by the eductor discharge plume may also have promoted the limestone dissolution rate.

12.3.3 Chloride Levels

Chloride-ion concentration during the TCA limestone forced oxidation tests ranged from 1000 to 3000 ppm, which is typical of previous tests without forced oxidation. As previously mentioned, the water balance and the tightness of the liquor loop were not significantly changed.

12.3.4 Eductor Performance

Air eduction by the eductor was as predicted by the manufacturer. The air eduction rate was sensitive to the back pressure (i.e., slurry submergence of the eductor) and ranged from 600 scfm at zero submergence to 200 scfm at 12 feet submergence at a 1600 gpm slurry rate. At 1600 gpm, the slurry pressure drop across the eductor was 38 psi. As seen from the two-tank runs in the TCA system, over 90 percent sulfite oxidation could be achieved at an air rate as low as 200 scfm.

The major operational problem in using the eductor for air/slurry contact resulted from the configuration of the eductor discharge hold tank. Because the residence time in the eductor is extremely short, most of the oxidation takes place in the hold tank. The 20-ft diameter hold tank was too large and normally operated at only a 6.1 ft slurry level to achieve 12 minutes' residence time. This slurry level was too shallow to allow time for the oxidation reaction to take place. At 8- and 12-ft slurry levels, over 90 percent oxidation could be achieved, but only by reducing the pH to increase the reaction rate.

If the eductor were discharged into a smaller but deeper tank, such as the oxidation tank in the venturi/spray tower system, good oxidation could probably be achieved at a higher pH and a lower slurry rate.

The eductor body was constructed of neoprene-lined carbon steel. The nozzle and the whirler were made of stellite. The rubber lined body was not satisfactory in slurry service with high fly ash loadings. After 1500 hours, the rubber had eroded in a circular pattern, presumably at the point of impact of the slurry from the nozzle. In a few spots, the rubber had worn to bare steel. Repair with Epoxylite 203 was unsuccessful. Without the rubber lining, the bare steel had eroded through after an additional 550 hours. The stellite nozzle and whirler showed only minor evidence of erosion.

12.4 SUMMARY OF FINDINGS

Nearly complete forced oxidation using an air eductor was achieved in the one-scrubber-loop TCA system with limestone slurry having high fly ash loading. The following is a summary of findings based on the results of these tests:

- Under the base case conditions of 30,000 acfm gas rate, 1200 gpm TCA slurry rate, 1600 gpm eductor slurry rate, 15 percent recirculated slurry solids (with fly ash), and an 8- to 12-ft slurry level in the effluent hold tank (oxidation tank), sulfite oxidation of better than 90 percent was achieved at eductor inlet pH range of 4.95 to 5.45 and air stoichiometric ratios as low as 2.0 atoms oxygen/mole SO_2 absorbed.
- The dewatering and handling characteristics of slurry solids oxidized to 90 percent or higher in a one-scrubber-loop system were as good as those in a two-scrubber-loop system.
- Operation in a two-tank configuration allowed for a higher pH to the TCA for good SO_2 removal and a lower pH to the eductor for good sulfite oxidation. Sulfite oxidations of up to 98 percent were achieved with satisfactory SO_2 removal (80 to 90 percent).
- With a single-tank configuration and limestone addition to the effluent hold tank, low hold tank pH (hence, low SO_2 removal) was necessary to achieve good sulfite oxidation. The SO_2 removal could be improved, however, by limestone addition to the TCA inlet slurry stream instead of the hold tank.

- SO_2 removal tended to be a few percentage points higher than the predicted SO_2 removal under similar operating conditions without forced oxidation. The reason for this removal enhancement is believed to be air stripping of CO_2 from the liquor, which increases the limestone dissolution rate.

- No significant difference in sulfite oxidation efficiency was observed between operations with the air eductor in the vertical, top-entry position or in the horizontal, bottom-entry position.

- Sulfite oxidation was unsatisfactory (about 60 percent) when the eductor slurry flow rate was reduced from 1600 to 1200 gpm. Decreased agitation in the oxidation tank at the lower flow rate, rather than the reduced air stoichiometric ratio, is believed to be the main reason for poor oxidation.

- Air eduction by the eductor was as predicted by the manufacturer. Air flow rate was sensitive to the depth of the eductor's submergence in the slurry, ranging from 600 scfm at zero submergence to 200 scfm at 12 ft submergence, at a 1600 gpm slurry rate. A flow of 200 scfm of air was sufficient to achieve good sulfite oxidation at 1600 gpm slurry flow.

- Air/slurry contact was hampered by the configuration of the eductor discharge hold tank (20-ft diameter tank with only 8 to 12 ft normal liquid depth). A smaller diameter but deeper tank would probably have given better oxidation efficiency.

- Erosion of the air eductor (in limestone/fly ash service) was a problem. The eductor body was constructed of neoprene-lined carbon steel. The rubber near the nozzle had eroded in a circular pattern after 1500 operating hours, and the carbon steel body had eroded through after an additional 550 hours. The stellite nozzle and whirler showed only minor evidence of erosion.

Section 13

TCA LIMESTONE TEST RESULTS WITH HIGH FLY ASH LOADING

The ultimate objective of this test block was to identify those test conditions that would allow compliance with the EPA SO_2 and particulate emission standards and at the same time permit reliable system operation. The efforts towards this objective culminated in Run 717-2A. Run 717-2A was preceded by two exploratory runs, Runs 715-2A and 716-2A.

13.1 LIMESTONE/HIGH FLY ASH RUN 715-2A

The test conditions for Run 715-2A (see Table 13-1 and Appendices H and I) were selected such that both the EPA SO_2 and particulate emission standards could be met. Three tanks in series were chosen to give good limestone utilization. A total static sphere height of 22.5 inches (3 beds at 7.5 inches/bed) was selected in order to meet the particulate emission standard. At this bed height and at a 30,000 acfm gas rate, the slurry flow rate had to be reduced to 1000 gpm from the normal 1200 gpm to avoid flooding.

SO_2 removal for the run averaged 86 percent at an average inlet SO_2 concentration of 3000 ppm and a limestone utilization of 81 percent. Average outlet particulate mass loading was 0.039 grain/dry scf.

Table 13-1

LIMESTONE TESTS WITH HIGH FLY ASH LOADING USING THREE TANKS IN SERIES ON THE TCA SYSTEM

Major Test Conditions	715-2A	716-2A	717-2A
Gas rate, acfm @ 300°F	30,000	27,000	Variable(2)
Liquor rate, gpm	1000	1000	1000
Percent solids recirculated	15	15	15
Total residence time (3 tanks), min.	14.4	14.4	14.4
TCA inlet pH controlled at	5.75	5.75	--
Stoichiometric ratio controlled at	--	--	1.2
Total static bed height (3 beds), inches	22.5	30	22.5
Selected Results			
Percent SO_2 Removal	86	91	87
Inlet SO_2 concentration, ppm	3000	2700	2800
Average outlet mass loading, gr/dry scf	0.039	0.025	0.043
Percent sulfite oxidation	21	25	22
TCA inlet pH	5.75	5.8	5.9
Percent limestone utilization	81	86	81
Percent gypsum saturation in TCA inlet liquor	100	105	90
Mist eliminator restriction, percent(1)	0	0	1
On stream hours	161	135	747

Notes:

(1) Continuous mist eliminator bottom wash with diluted clarified liquor. Wash rate was 0.4 gpm/ft^2 for Runs 715-2A and 716-2A and 0.3 gpm/ft^2 for Run 717-2A.

(2) Gas rate varies between 20,000 and 30,000 acfm, depending on the No. 10 boiler load.

Both the SO_2 and particulate emission standards were met during Run 715-2A, although not by a comfortable margin.

13.2 LIMESTONE/HIGH FLY ASH RUN 716-2A

Although the particulate emission during Run 715-2A met the EPA standard, the particulate emission level would probably give very poor opacity if extrapolated to a 500 MW size stack. It is estimated that to get a 20 percent opacity (for a 500 MW stack), an outlet mass loading of about 0.02 grain/dry scf, or less, would be required.

Run 716-2A (see Table 13-1 and Appendices H and I) was made with 30 inches total static bed height (3 beds at 10 inches/bed) to observe whether an outlet mass loading of 0.02 grain/dry scf, or less, could be achieved. The flue gas flow rate had to be reduced from 30,000 to 27,000 acfm to avoid flooding of the scrubber at 1000 gpm slurry flow rate and 30 inches total bed height.

Average outlet particulate mass loading decreased to 0.025 grain/dry scf for Run 716-2A, short of the 0.02 grain/dry scf target. SO_2 removal averaged 91 percent at 2700 ppm inlet SO_2 and 86 percent limestone utilization. The improvements in both SO_2 and particulate removal resulted, of course, from the higher scrubber pressure drop (10 to 12.5 inches H_2O for Run 715-2A versus 12.8 to 16.1 inches H_2O for Run 716-2A).

13.3 LIMESTONE/HIGH FLY ASH RELIABILITY RUN 717-2A

During October/November 1977, Run 717-2A, a one-month limestone slurry reliability run, was made in the TCA system. This run was conducted over 747 hours (31-1/8 days), and was designed to demonstrate operating reliability of the scrubber system with respect to scaling and plugging and to determine if the EPA New Source Performance Standards for SO_2 and particulate emissions could be met. The fan damper, the outlet duct to the reheater, the bottom bar grid, and the scrubber walls below the bottom grid were cleaned before the run. Detailed operating conditions and test results for Run 717-2A are presented in Appendices H and I.

The run was made without forced oxidation and with flue gas containing high fly ash loading. Three hold tanks in series with a total residence time of 14.4 minutes were used to improve the limestone utilization. The flue gas flow rate was varied between 20,000 and 30,000 acfm (gas velocity between 8.4 and 12.5 ft/sec) according to the No. 10 Boiler load, which normally fluctuated between 100 and 155 MW. The slurry flow rate was constant at 1000 gpm; the recirculated slurry solids concentration was 15 weight percent. The limestone stoichiometric ratio was controlled at 1.2 moles Ca/mole SO_2 absorbed by the automatic limestone feed system. Three beds were used, with 7.5 inches static height of nitrile foam spheres in each bed.

A total of three scheduled inspections were made during the run. These inspections normally lasted less than 5 hours. During the third inspection on November 14, the scrubber was down for 5 extra hours so that a problem on the limestone feeder weigh belt could be resolved. This was the only scrubber unavailable time during Run 717-2A, giving a scrubber availability of 99.3 percent excluding the downtime for scheduled inspections.

Average SO_2 removal for the entire run was 87 percent at 2800 ppm average inlet SO_2 concentration. This average removal efficiency was higher than the 84 percent required to meet the 1.2 lb SO_2/MM Btu emission standard. However, the standard was exceeded frequently for periods greater than the three hours allowed by EPA regulations due to wide fluctuations in inlet SO_2 concentration and slow system or operating response time.

At the controlled limestone stoichiometric ratio of 1.2, the TCA inlet pH averaged 5.9 and the limestone utilization averaged 81 percent. Sulfite oxidation was 22 percent.

The outlet particulate loading during Run 717-2A ranged from 0.026 to 0.069 grain/dry scf, with a run average of 0.043 grain/dry scf. Assuming a 30 percent boiler excess air, the outlet particulate loading should be 0.052 grain/dry scf or less to meet the emission standard of 0.10 lb particulate/ MM Btu.

The mist eliminator was entirely clean at the beginning of the run. Routine inspection showed that it was 1 percent restricted by solids after 161 on-stream hours, 2 percent after 350 hours, entirely clean after 587 hours, and 1 percent after 747 hours at the end of the run. There was no significant increase in solids deposits on the scrubber internals during the run.

In summary, reliable operation of the TCA system was demonstrated during Run 717-2A. However, as in the venturi/spray tower reliability limestone Run 819-1A, the scrubber performance did not meet the EPA new source SO_2 and particulate emission standards at all times, even though the run-averaged SO_2 and particulate emissions met these regulations.

Section 14

CEILCOTE SUPPORT PLATE PACKING TESTS ON THE TCA SYSTEM

14.1 INTRODUCTION

After completion of the TCA long-term limestone reliability run, Run 717-2A, two weeks were needed to complete the installation of an air-sparging system for forced-oxidation testing. The Shawnee Project Steering Committee decided that during these two weeks a series of short tests would be conducted using scrubber internals other than the 1-5/8 inches, 6.5 gram solid nitrile foam spheres.

An egg-crate type plate (packing support plate) manufactured by Ceilcote Company was selected. The plate dimensions were 2 feet x 2 feet x 2 inches, with a 1-3/16 inch square opening. They were made of fiberglass filled polypropylene. The nitrile foam spheres in the TCA were removed with the four bar grids remaining in the scrubber. Twenty-three layers of Ceilcote plates (46 inches in height) were installed between the second and third bar grids.

The number of plate layers was selected to give an estimated pressure drop of 8 inches H_2O (including the four grids) at a 30,000 acfm gas rate and a 1200 gpm slurry flow rate. This is a typical pressure drop obtained under these flow rates for a three-bed, four-grid TCA with 5-inch static height of spheres per bed. This arrangement allows a direct comparison of scrubber performances between the plate packing and the mobile spheres. The objective of these tests was to obtain preliminary data on the SO_2 and particulate removal efficiency for the selected packing. Due to the short duration of the tests, it was not expected that sufficient information for assessing the reliability of this packing with respect to scaling and plugging would be obtained.

14.2 TEST PLAN

Two one-week test runs were made. The first test (Run 718-2A, see Subsection 2.4) was made under the following typical TCA operating conditions so that the SO_2 and particulate removal data could be directly compared with those of a TCA scrubber:

- 30,000 acfm gas rate
- 1200 gpm slurry flow rate
- High fly ash loading
- 15 percent solids in recirculated slurry
- 12 minutes slurry residence time
- 1.2 limestone stoichiometric ratio on automatic control

The second test (Run 719-2A) was made under the same conditions as the first, except that the gas rate was reduced to 18,000 acfm to observe the turndown capability of the plate packing.

14.3 RESULTS OF RUNS 718-2A AND 719-2A

SO_2 removal for Run 718-2A, as shown in Table 14-1, averaged 76 percent at 3200 ppm average inlet SO_2 concentration. The inlet pH averaged 5.75 and limestone

Table 14-1

LIMESTONE TESTING ON THE TCA SYSTEM
WITH CEILCOTE PLATE PACKING

Major Test Conditions	718-2A	719-2A
Gas rate, acfm @ 300°F	30,000	18,000
Liquor rate, gpm	1200	1200
Percent solids recirculated	15	15
Residence time, min.	12	12
Stoich. ratio controlled at	1.2	1.2
Height of plate packing, inches	46	46
Selected Results		
Percent SO_2 removal	76	86
Inlet SO_2 concentration, ppm	3200	3050
Average outlet mass loading, gr/dry scf	0.042	0.057
Percent sulfite oxidation	21	19
TCA inlet pH	5.75	5.75
Percent limestone utilization	75	86
Percent gypsum sat'n in TCA inlet liquor	110	105
Mist eliminator restriction, percent	0.05	0.5

utilization averaged 75 percent. The flue gas pressure drop across the 23 layers (46 inches) of Ceilcote plates and four bar grids, measured in a series of pressure drop tests conducted prior to the runs (see Figure 14-1), was 7.2 inches H_2O or about 10 percent less than estimated before these tests.

Under similar operating conditions, a three-bed, four-grid TCA with 5 inches static height of 1-5/8 inch diameter solid nitrile foam spheres per bed (about 9 inches H_2O flue gas pressure drop) would give about 80 percent SO_2 removal, (Reference 3) somewhat better than the plate packing.

Run 719-2A (see Table 14-1) was similar to Run 718-2A except that the gas rate was reduced from 30,000 to 18,000 acfm to compare the turndown capacity of the Ceilcote plate packing with that of the 1-5/8 inch diameter, 6.5-gram solid nitrile foam spheres. Average SO_2 removal for this run was 86 percent at an average inlet SO_2 concentration of 3050 ppm. The inlet pH averaged 5.75 and limestone utilization averaged 86 percent. Flue gas pressure drop across the plates and four bar grids as shown in Figure 14-1 averaged about 2.9 inches H_2O.

Under the same operating conditions, a three-bed, four-grid TCA with 5 inches of spheres per bed (about 4.5 inches H_2O flue gas pressure drop) gives about 78 percent SO_2 removal. Thus, when compared with a TCA unit operating with spheres, SO_2 removal is slightly worse at high gas rates, but the turndown capacity is significantly better. The better turndown capacity can be attributed to a reduction of the sphere activity, and therefore the gas-slurry contact, as the gas flow rate is reduced.

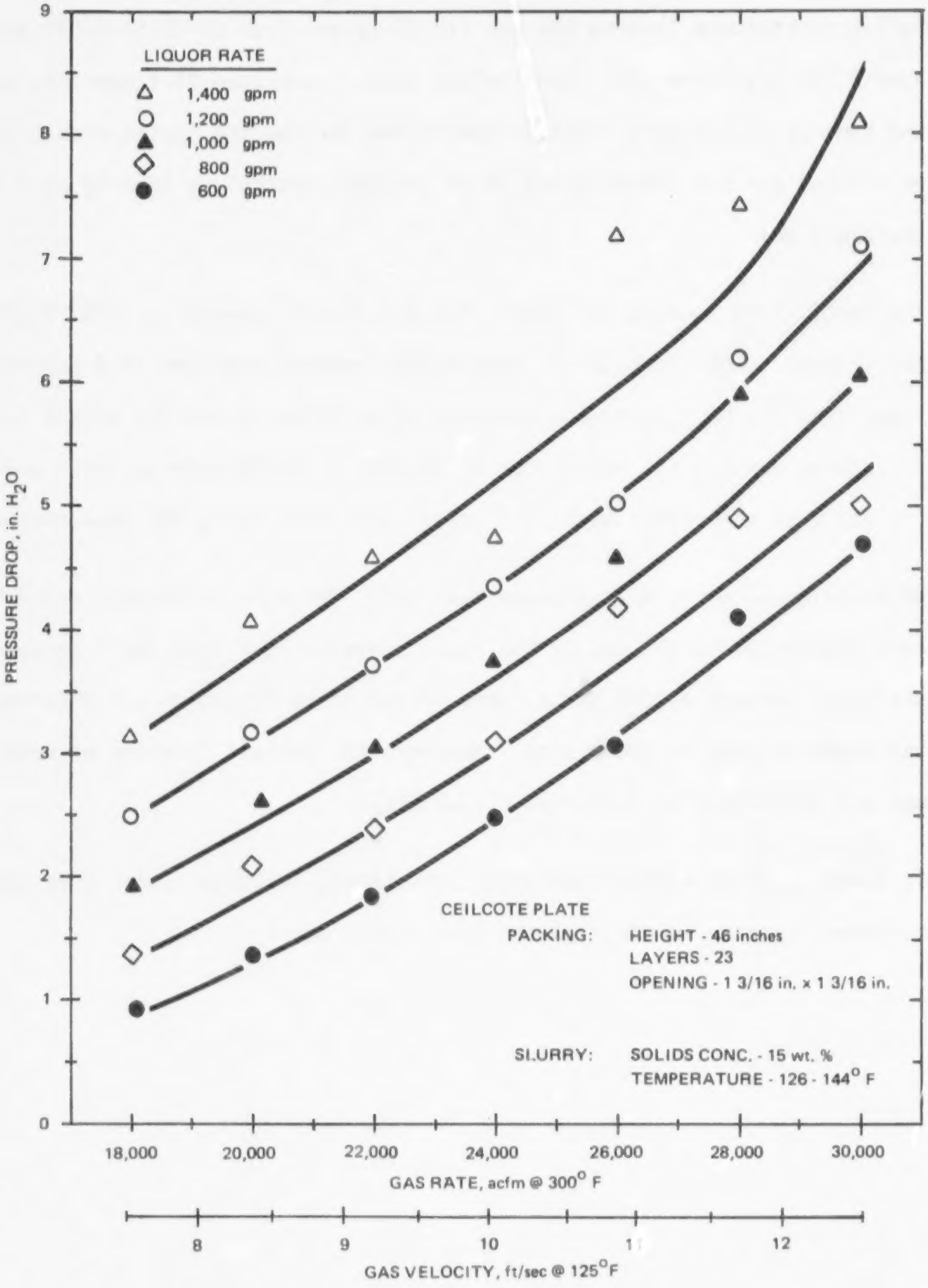


Figure 14-1. Pressure Drop Across Four Bar Grids and Twenty-three Layers of Ceilcote Support Plate Packing

Outlet particulate loading for Run 718-2A ranged from 0.038 to 0.046 and averaged 0.042 grain/dry scf. Particulate removal averaged 98.9 percent, exactly the same as it did under similar conditions for the TCA system with 5 inches of spheres per bed (three beds) at an average particulate loading of 0.064 grain/dry scf.

The particulate loading was higher for Run 719-2A, averaging 0.057 grain/dry scf (range: 0.050 to 0.065). Particulate removal averaged 98.4 percent, lower than the 99.1 percent previously experienced by the TCA with 5 inches of spheres per bed for three beds at nominally 20,000 acfm gas rate and continuous mist eliminator wash, all other conditions being the same (Reference 4).

No plugging occurred during these two runs. The mist eliminator was 0.5 percent restricted at the end of the runs, somewhat less than the 1 percent restriction present before these runs. Minor scale formation was observed along the edges of some of the plates. However, the overall duration of both runs was not sufficient to determine reliability.

In summary, under similar operating conditions, Ceilcote plates gave better turndown capacity for SO_2 removal than sphere beds.

Section 15

TCA ONE-SCRUBBER-LOOP FORCED-OXIDATION LIMESTONE TESTS WITH AIR SPARGER

The results of TCA one-scrubber-loop forced-oxidation limestone tests using an air eductor for air/slurry contact have been reported in Section 12. Erosion of the air eductor used in those tests was a major problem. Testing was terminated after about 2050 hours when the neoprene-lined carbon steel eductor body had eroded through.

In this section, the results of forced-oxidation tests using an air sparger are reported. The TCA system was operated in a one-scrubber-loop configuration employing either one or two tanks. The air sparger had 40 1/4-inch diameter holes, similar to the one used in the venturi/spray tower system.

As in the testing with the air eductor, only limestone slurry with high fly ash loading was used. Forced oxidation within the scrubber loop using lime slurry would not be expected to yield good SO_2 removal, as has been mentioned previously. Seven runs were made from December 9, 1977 through January 24, 1978, using limestone slurry with high fly ash loading. In addition, one run was made with limestone slurry and added MgO from May 31 through June 8, 1978. Each test lasted about 6 days.

Table 15-1 summarizes the major test conditions and the important test results. Detailed information concerning these runs can be found in Appendices B through D, and H through J.

Table 15-1

SUMMARY OF ONE-SCRUBBER-LOOP FORCED-OXIDATION LIMESTONE TESTS WITH AIR SPARGER ON THE TCA SYSTEM

Major Test Conditions[2]	815-2A	816-2A	817-2A	818-2A	818-2B	819-2A	820-2A	821-2A
Fly ash loading	High	High	High	High	High	High	High	High
Flue gas rate, acfm @ 300°F	30,000	30,000	20,000	25,000	25,000	20,000	20,000	30,000
Slurry flow rate to TCA, gpm	1000	1000	1000	1000	1000	1000	1000	1200
Percent solids recirculated	15	15	15	15	15	15	15	15
Residence times, min: Oxidation tank	5.2	5.2	5.2	5.2	5.2	4.9	4.9	4.1
EHT	14.4	14.4	14.4	14.4	14.4	-	-	-
Oxidation tank level, ft	18	18	18	18	18	17	17	17
Air flow rate to oxidation tank	130	180	130	130	0	130	130	170
Limestone stoichiometric ratio (controlled)	1.3	1.3	1.3	1.3	1.3	1.3	-	1.2
TCA inlet pH (controlled)	-	-	-	-	-	-	5.9	-
Effective Mg^{++} concentration, ppm	-	-	-	-	-	-	-	5000
Limestone addition point	EHT	EHT	EHT	EHT	EHT	Oxid. Tk	Oxid. Tk	Oxid. Tk
Total static height of spheres, inches	20	22.5	22.5	22.5	22.5	22.5	22.5	15
Selected Results								
Percent SO_2 removal	89	91	79	85	82	75	79	84
Inlet SO_2 concentration, ppm	3000	2850	3000	3000	3300	2800	2500	2500
Percent sulfite oxidation	40	54	94	67	24	94	92	95
Air stoichiometry, atoms O/mole SO_2 absorbed	1.0	1.40	1.70	1.25	0	1.90	2.0	1.65
TCA inlet pH	6.25	6.25	5.8	6.2	6.2	5.55	5.65	5.35
Oxidation tank pH	-	5.7	5.45	5.65	-	5.55	5.65	5.35
Limestone utilization, %	80	76	81	77	81	77	62	79
Gypsum saturation in TCA inlet liquor, %	110	100	100	95	110	110	115	110
Effective Mg^{++} concentration, ppm	-	-	-	-	-	-	-	4960
Onstream hours	75	48	161	131	140	164	259	182

Notes:

(1) Used a sparger ring located 8 inches from the bottom of oxidation tank. The sparger ring had 40 1/4-inch diameter holes on the bottom side.
(2) Clarifier only was used for solids dewatering except for Run 821-2A in which clarifier and centrifuge were used. Centrifuge cake solids concentration was 79 percent.

15.1 SYSTEM DESCRIPTION

Two operating configurations were used in the one-scrubber-loop forced-oxidation tests. With one tank, as shown in Figure 15-1, effluent slurry from the TCA was discharged to the oxidation tank, where limestone (and MgO during Run 821-2A) was added, and the slurry was recycled back to the TCA. With two tanks in series, as shown in Figure 15-2, TCA effluent slurry was discharged to the oxidation tank and the slurry then overflowed to a second tank (effluent hold tank), where limestone was added and slurry was recycled from the second tank back to the TCA.

Although the one-tank configuration is simpler and modification of the existing full-scale installations to this forced oxidation scheme can be made readily (with the addition of an air sparger and a compressor or blower), a balance must be made in the single tank between the higher pH desired for good SO_2 removal and the lower pH desired for good sulfite oxidation. The two-tank configuration has the advantage of oxidizing the lower pH scrubber effluent slurry before limestone is added. The two-tanks-in-series mode also provides better limestone utilization.

The oxidation tank arrangement is shown in Figure 15-3. The tank was 7 feet in diameter and was operated at a 17- to 18-feet level. All tests were conducted with an air sparger ring made of straight 3-inch 316L SS pipe pieces welded into an octagon of approximately 4-feet diameter. The ring was located 8 inches from the bottom of the tank and had 40 1/4-inch diameter holes pointed downward. The sparger ring was fed with compressed air to which sufficient water was added to assure humidification.

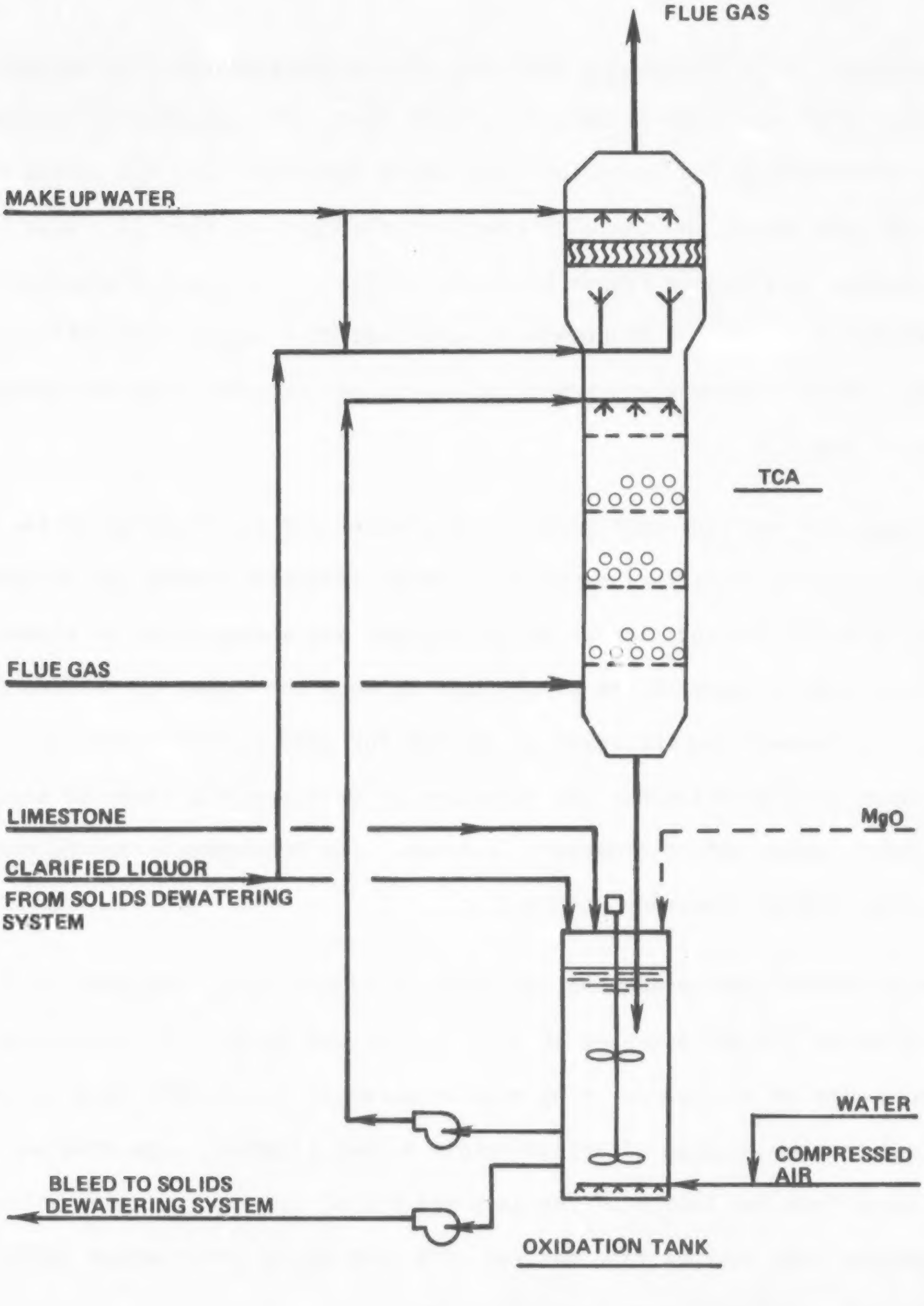

FLUE GAS
MAKE UP WATER
TCA
FLUE GAS
LIMESTONE
MgO
CLARIFIED LIQUOR
FROM SOLIDS DEWATERING SYSTEM
WATER
COMPRESSED AIR
BLEED TO SOLIDS DEWATERING SYSTEM
OXIDATION TANK

Figure 15-1. Flow Diagram for One-Scrubber-Loop Forced Oxidation with Air Sparger in the TCA System Using One Tank

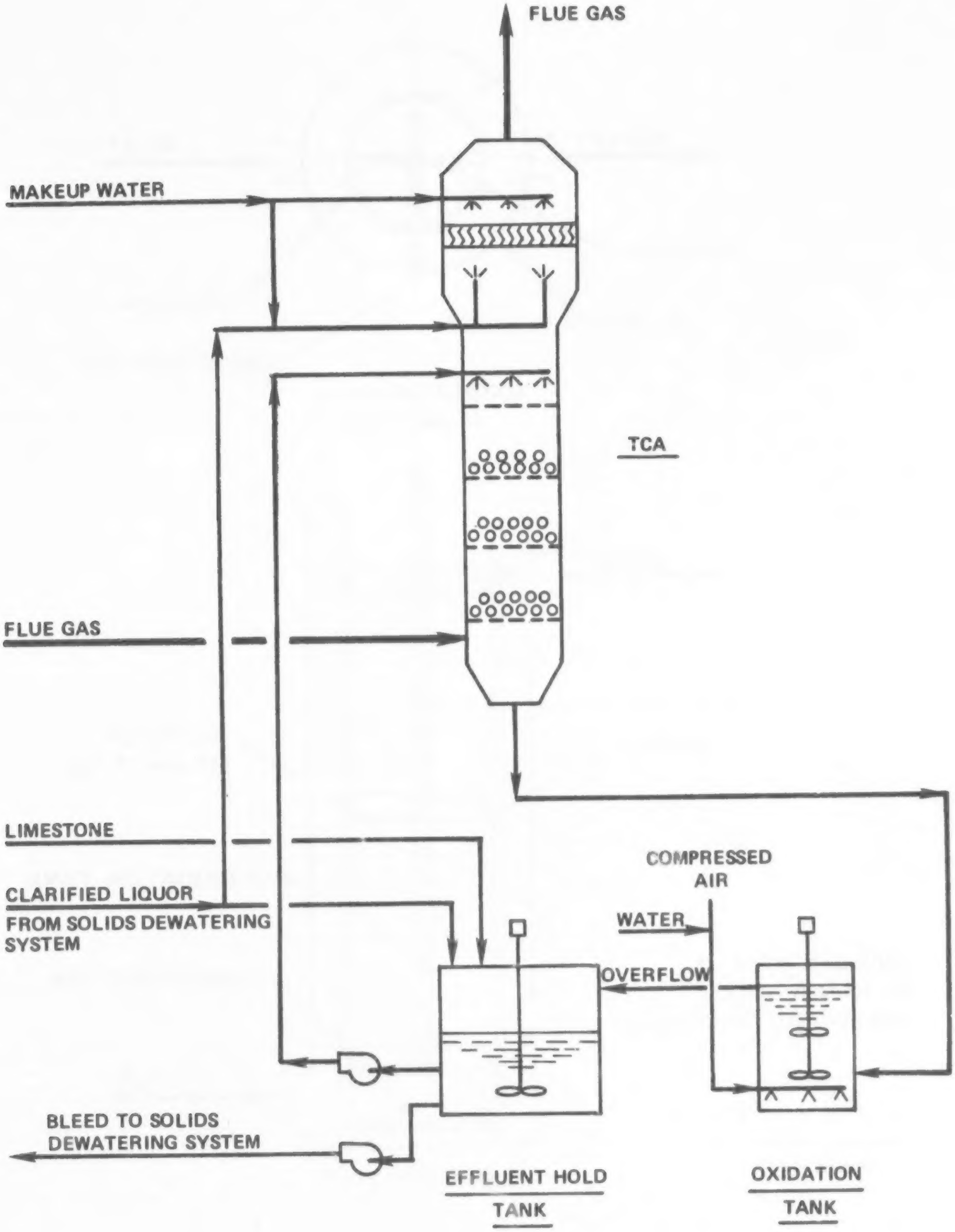

FLUE GAS
MAKEUP WATER
TCA
FLUE GAS
LIMESTONE
COMPRESSED AIR
CLARIFIED LIQUOR FROM SOLIDS DEWATERING SYSTEM
WATER
OVERFLOW
BLEED TO SOLIDS DEWATERING SYSTEM
EFFLUENT HOLD TANK
OXIDATION TANK

Figure 15-2. Flow Diagram for One-Scrubber-Loop Forced Oxidation with Air Sparger in the TCA System Using Two Tanks

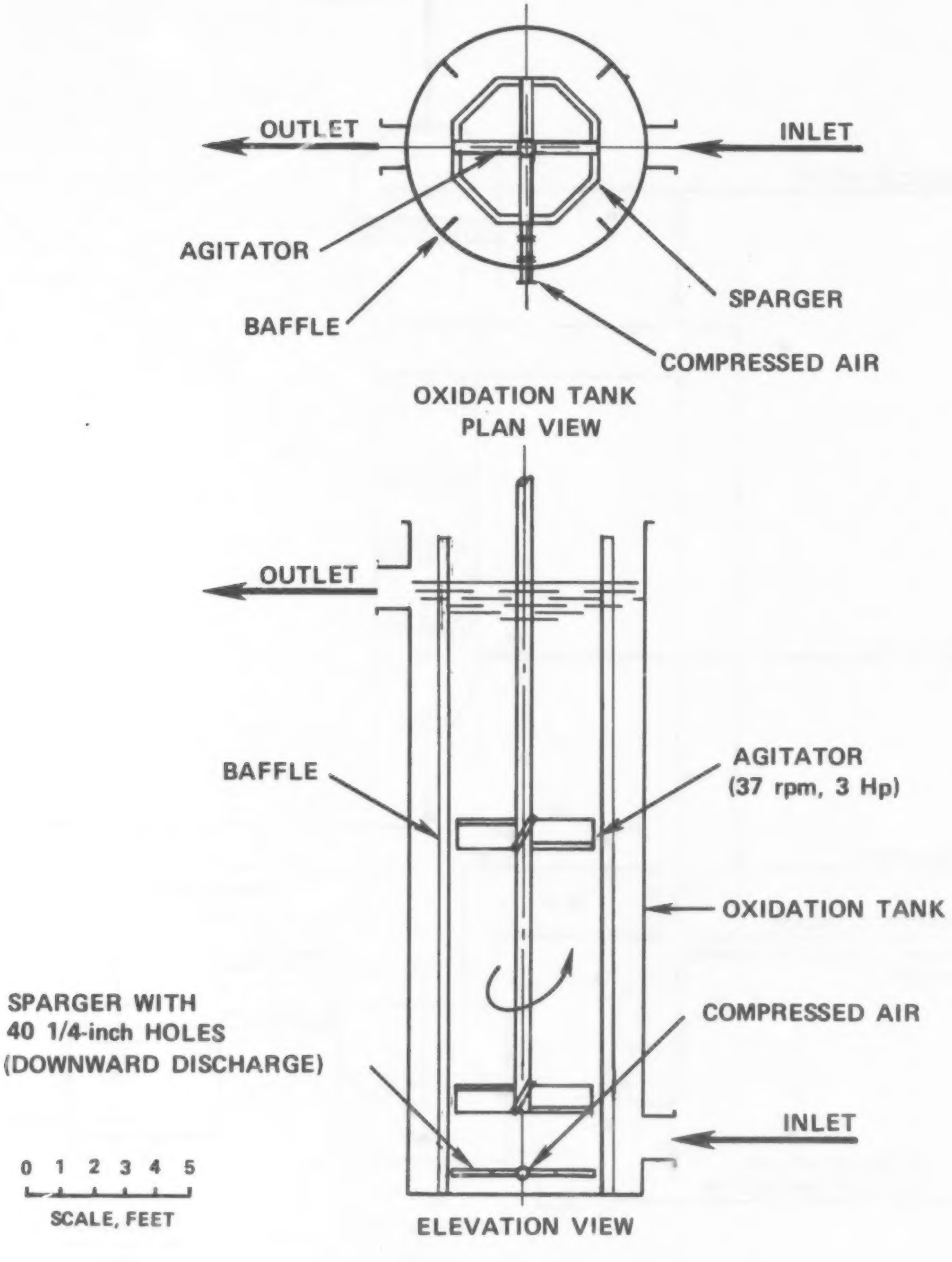

OUTLET
INLET
AGITATOR
BAFFLE
SPARGER
COMPRESSED AIR
OXIDATION TANK
PLAN VIEW
OUTLET
BAFFLE
AGITATOR
(37 rpm, 3 Hp)
OXIDATION TANK
SPARGER WITH
40 1/4-inch HOLES
(DOWNWARD DISCHARGE)
COMPRESSED AIR
INLET
0 1 2 3 4 5
SCALE, FEET
ELEVATION VIEW

Figure 15-3. Arrangement of the TCA Oxidation Tank with Air Sparger

A major shortcoming of this oxidation system was that the agitator was rated at only 3 Hp and rotated at 37 rpm (compared with 17 brake Hp and 56 rpm for the venturi oxidation tank). This agitator was similar in configuration to the agitator in the venturi oxidation tank with two axial flow turbines (49 inches in diameter) pumping downward. Because of the weaker agitation, runs with similar oxidation tank environment (pH, air stoichiometry, tank level, percent slurry solids, and limestone utilization) had lower oxidation efficiency in the TCA oxidation tank than in the venturi oxidation tank.

A 20-Hp variable speed agitator is on order and will be used to determine the relationship between oxidation tank agitation and air requirements.

A second shortcoming was that the existing Shawnee air compressor did not have sufficient capacity to serve the venturi and the TCA oxidation tanks simultaneously at full flue gas load. To circumvent this problem, several of the TCA runs were made at reduced flue gas flow rates. An additional air compressor has been ordered to correct this limitation.

A clarifier was used for solids dewatering in all runs except Run 821-2A. In that run, a clarifier followed by a centrifuge was used.

15.2 DISCUSSIONS OF TEST RUN RESULTS

15.2.1 Air Stoichiometry

Runs 815-2A through 818-2B were made with two hold tanks in series as shown in Figure 15-2. The primary effort during these runs was to identify the air stoichiometric ratio required for nearly complete oxidation. In the first two test runs, operated at the maximum achievable flue gas flow rate of 30,000 acfm, it was found that the air compressor did not have a high enough capacity to supply both the venturi/spray tower system and the TCA system. With an air rate of 210 scfm to the venturi oxidation tank, only 180 scfm was available for the TCA system. Further tests were conducted at reduced flue gas flow rates (20,000 to 25,000 acfm) to allow higher air stoichiometry at the available air rate. The results of these tests conducted over an oxidation tank pH range of 5.4 to 5.7 were as follows:

Run	Air Stoichiometric Ratio, atoms oxygen/mole SO_2 absorbed	Percent Sulfite Oxidation
817-2A	1.7	94
816-2A	1.4	54
818-2A	1.25	67
815-2A	1.0	40
818-2B	0	24

Thus, with two hold tanks in series, an air stoichiometric ratio of about 1.7 was required to achieve greater than 90 percent oxidation. Under similar conditions in the venturi oxidation tank, higher oxidation efficiency (95 to 100) percent) was achieved. This better performance in the venturi oxidation tank was attributed to the superior agitation in the venturi oxidation tank.

Runs 819-2A and 820-2A were made with the oxidation tank as the only hold tank as shown in Figure 15-1. In these runs, the pH in the oxidation tank was higher as a result of limestone addition. Because of the higher pH, a higher air stoichiometry was required. This effect can be seen by comparing Runs 817-2A (two hold tanks) and 819-2A (one hold tank) made at essentially the same operating conditions. In both runs, 94 percent sulfite oxidation was achieved. An air stoichiometric ratio of 1.7 atoms oxygen/mole SO_2 absorbed was used in the run with two hold tanks (5.45 oxidation tank pH), and an air stoichiometry of 1.9 was required in the run with one hold tank (5.55 oxidation tank pH). Run 820-2A, at still higher oxidation tank pH of 5.65, achieved only 92 percent oxidation at 2.0 air stoichiometry.

15.2.2 SO_2 Removal Efficiency

At given limestone stoichiometric ratios, SO_2 removal efficiency appeared to be independent of oxidation efficiency, and was primarily a function of flue gas flow rate, slurry flow rate, and inlet SO_2 concentration. This relationship agreed closely with previously developed correlations for the TCA system in limestone service without forced oxidation. At 3000 ppm inlet SO_2 concentration and a limestone stoichiometric ratio controlled at 1.3 moles Ca/mole of SO_2 absorbed, SO_2 removal efficiency ranged from about 90 percent at 30,000 acfm to about 80 percent at 20,000 acfm. In general, two-tank operation gave better SO_2 removal than one tank.

15.2.3 Limestone Utilization

Limestone utilization was higher in the runs using two tanks in series than in the single-tank runs. Again comparing Runs 817-2A and 819-2A, limestone utilization was 77 percent with one tank and 81 percent with two tanks even though the inlet pH was lower with one tank. SO_2 removal efficiency was also improved from 75 percent with one tank to 79 percent with two tanks. The improvement can be attributed to higher residence time (19.6 minutes total with two tanks versus 4.9 minutes with one tank) and the approach to plug flow inherent with tanks in series.

Because of the relatively poor SO_2 removal efficiency in Run 819-2A, the next run (Run 820-2A) was made at a slightly higher pH. The oxidation tank pH was increased from 5.55 to 5.65. SO_2 removal increased only slightly from 75 percent at 2800 ppm inlet SO_2 concentration to 79 percent at 2500 ppm. However, the limestone utilization decreased from 77 percent to 62 percent.

15.2.4 MgO Addition

The addition of MgO should not enhance SO_2 removal in a scrubber loop with forced oxidation (see Section 6). This was demonstrated in Run 821-2A. Magnesium ion in the scrubber liquor improves SO_2 removal by increasing the sulfite ion, an effective SO_2 scrubbing component, but forced oxidation converts the sulfite to sulfate, which is nonreactive.

In Run 821-2A, with 4960 ppm effective magnesium ion concentration and with forced oxidation, the SO_2 removal efficiency averaged 84 percent, which was no higher than expected without MgO addition. In a previous run with MgO addition the same as in Run 821-2A but without forced oxidation, SO_2 removal averaged 92 percent. Thus, the enhancement on SO_2 removal with MgO addition is not achieved in a scrubber loop with forced oxidation.

15.2.5 General Operating Characteristics

The general operating characteristics of the one-scrubber-loop system with forced oxidation using an air sparger were the same as those using an air eductor (see Subsection 12.3) with regard to the water balance and the chloride levels. In Run 821-2A, the liquor loop was tighter because of the use of the centrifuge in series with the clarifier to minimize magnesium oxide consumption.

An air sparger does not, of course, have the severe erosion problems associated with an air eductor, and it also consumes less energy than an eductor due to lower pressure drop. This latter advantage of air sparger on energy consumption may also hold true when considering the sparger/agitator and eductor/agitator combination, even though the eductor discharge plume provides significant mixing in the oxidation tank.

15.3 SUMMARY OF FINDINGS

Despite oxidation tank agitator and air compressor limitations, forced oxidation with an air sparger in a one-scrubber-loop TCA system was demonstrated. The following is a summary of findings.

- With two tanks in series, 94 percent sulfite oxidation was achieved at an air stoichiometry of 1.7, oxidation tank pH of 5.45, and an oxidation tank level of 18 feet. Under a similar oxidation tank environment, higher oxidation efficiency (95 percent or over) was achieved in the venturi oxidation tank. The poorer performance on the TCA system was attributed to the weaker agitation in the TCA oxidation tank.
- Because of higher pH in a one-tank configuration, higher air stoichiometry (about 1.9) was required to achieve a similar degree of oxidation (94 percent).
- Operation in the two-tank mode gave better limestone utilization and SO_2 removal than operation in the one-tank mode.
- As expected, MgO addition did not enhance the SO_2 removal when oxidation was forced within the scrubber loop (Run 821-2A).

Further tests will be conducted in the future when a higher speed agitator for the oxidation tank and a new air compressor are installed on the TCA system.

Section 16

TCA LIMESTONE/MgO TEST RESULTS

Because of insufficient compressed air capacity for forced oxidation with an air sparger in the TCA system (see Section 15), further testing with forced oxidation of the TCA system was deferred until a new air compressor could be installed.

Beginning in late January 1978 through the end of the report period, the TCA system was operated without forced oxidation using lime or limestone slurry with added MgO. The primary purpose of these tests was to resolve some of the inconsistent results obtained in the earlier lime/MgO tests (Runs 601-2A through 617-2A) and limestone/MgO tests (Runs 583-2A through 589-2A), in which air leakage into the scrubber downcomer was suspected during some runs, resulting in higher than expected sulfite oxidation and gypsum scaling (see Sections 10 and 11, Reference 4).

In those earlier tests, made from April through November 1976, a 7-ft diameter by 21-ft high effluent hold tank (D-204) was used in a majority of runs. The scrubber downcomer inside the effluent hold tank (the internal downcomer) discharged the scrubber effluent slurry at an elevation of 14 ft above the tank bottom. Since the scrubber operated below atmospheric pressure, those runs having a tank level less than 14 ft (to maintain low residence times) experienced some air leakage via the downcomer. The air leakage was indicated by the fact that sulfite oxidation was 10 to 15 percentage points higher than normal for those runs, resulting in high gypsum saturation and scaling problems.

To avoid the air leakage problem with the internal downcomer at tank levels below 14 ft, an external downcomer was installed in August 1977. The external downcomer branches off the existing internal downcomer and enters the effluent hold tank (D-204) radially near the tank bottom, thus preventing air leakage. Blank plates are provided to allow either downcomer to be used.

16.1 DISCUSSIONS OF TEST RUN RESULTS

The results of limestone tests with MgO addition are presented in this section. Lime tests with MgO addition are reported in Section 17.

A total of six limestone runs were made from late January through early May 1978, including two base case runs without MgO and four runs with MgO addition. Flue gas with high fly ash loading was used in all runs. Table 16-1 presents the major test conditions and important test results. Additional detailed information can be found in Appendices B through D, and H through J.

Because of the shortage of coal caused by the coal miners' strike in the first quarter of 1978, coals from different sources were burned in Boiler No. 10. As a result, inlet SO_2 concentration fluctuated as much as tenfold (320 to 3400 ppm), and the run-average concentrations were considerably lower than normal in most of the runs. These wide variations in inlet SO_2 concentration not only created process control problems, but also caused some difficulties in the interpretation of run data and in the run-to-run comparison of test results.

Table 16-1

SUMMARY OF LIMESTONE TESTS WITH MgO ADDITION ON THE TCA SYSTEM

Major Test Conditions(1)	590-2A	590-2B	591-2A	592-2A	593-2A	594-2A
MgO addition	No	No	Yes	Yes	Yes	Yes
Fly ash loading	High	High	High	High	High	High
Gas rate, acfm @ 300°F	30,000	30,000	30,000	30,000	30,000	30,000
Slurry flow rate to TCA, gpm	1200	1200	1200	1200	900	1200
Percent solids recirculated	15	15	15	15	15	15
EHT residence time, min(2)	4.1	4.1	4.1	4.1	4.1	4.1
EHT level, ft(2)	17	17	17	17	12.8	17
Downcomer to EHT(2)	Ext.	Int.	Ext.	Ext.	Ext.	Int.
Limestone stoichiometric ratio (controlled)	1.2	1.2	1.2	1.2	1.2	1.2
Limestone addition point(3)	DC	DC	EHT	EHT	EHT	EHT
Effective Mg^{++} concentration, ppm	0	0	5000	9000	9000	9000
Selected Results						
Percent SO_2 removal	64	77	92	95	93	93
Inlet SO_2 concentration,ppm	2100	2450	2300	2850	2850	2850
SO_2 make-per-pass, m-moles/liter	7.3	9.9	11.3	13.8	18.8	13.8
TCA inlet liquor sulfite concentration, ppm(4)	770	270	2000	4360	4855	5370
TCA inlet liquor gypsum saturation, %	110	120	105	105	85	90
Percent sulfite oxidation	45(5)	31	43	25	24	18
Percent limestone utilization	88	85	80	74	63	81
TCA inlet pH	5.0	5.3	5.5	5.4	5.45	5.35
Effective Mg^{++} concentration, ppm	0	0	4930	8870	9000	8950
Onstream hours	45	92	207	293	260	99

Notes:

(1) All runs were made with 3 beds (4 grids) and with nominally 5 inches/bed of 1 5/8 inch diameter nitrile foam spheres. Clarifier and centrifuge were used for solids dewatering in all runs.

(2) The effluent hold tank (D-204) was 7 ft in diameter and 21 ft high. Tests were made with either an internal or external downcomer.

(3) EHT or downcomer (DC).

(4) Total sulfite includes $SO_3^=$ and HSO_3^-.

(5) Steady-state sulfite oxidation was not reached during Run 590-2A.

16.1.1 Base Case Runs 590-2A and 590-2B

Runs 590-2A and 590-2B were base case limestone runs without MgO addition. The operating conditions for these runs were the same except for the difference in the downcomer used. Run 590-2A with the external downcomer was terminated after only 45 hours of operation because of severe cold weather and freezing problems. Because of the short duration of the run, steady-state natural sulfite oxidation level was not reached from the nearly complete oxidation level of a previous forced-oxidation test (Run 820-2A). Run 590-2B was a continuation of Run 590-2A, except that the internal downcomer had to be used because the external downcomer was frozen.

The results of Run 590-2B are compared below with those of a similar test, Run 583-2A, which was a base case limestone run for the limestone/MgO tests made in 1976 (Reference 4).

	590-2B	583-2A
EHT residence time, min	4.1	3.0
EHT level, ft	17	12.5
Downcomer to EHT	Int.	Int.
Air leakage	No	Yes
Percent SO_2 removal	77	77
Inlet SO_2 concentration, ppm	2450	3050
SO_2 make-per-pass, m-moles/liter	9.9	12.5
Percent sulfite oxidation	31	34
TCA inlet liquor gypsum sat'n, %	120	145

Other operating conditions for the two runs were the same. Sulfite oxidation in Run 583-2A was 34 percent, which was higher than normal because of the air leakage. However, oxidation for Run 590-2B was also relatively high at 31 percent, probably due to the lower inlet SO_2 concentration (higher O_2/SO_2 ratio in the inlet flue gas). The higher TCA inlet liquor gypsum saturation of 145 percent for Run 583-2A was consistent with the higher sulfite oxidation.

16.1.2 Effect of MgO Addition

In Run 591-2A, magnesium oxide was added to maintain an effective Mg^{++} concentration* of 5000 ppm. SO_2 removal increased from 77 percent at 2450 ppm without MgO addition for Run 590-2B to 92 percent at 2300 ppm inlet SO_2 concentration. At 9000 ppm effective Mg^{++} concentration (Runs 592-2A and 594-2A), average SO_2 removal was 93 to 95 percent at a higher inlet SO_2 concentration of 2850 ppm.

Run 591-2A is compared below with a similar test, Run 583-2B, made in 1976 (Reference 4).

	591-2A	583-2B
EHT residence time, min	4.1	3.0
EHT level, ft	17	12.5
Downcomer to EHT	Ext.	Int.
Air leakage	No	Yes
Percent SO_2 removal	92	84
Inlet SO_2 concentration, ppm	2300	2900
SO_2 make-per-pass, m-moles/liter	11.3	13.5
Percent sulfite oxidation	43	30
TCA inlet liquor gypsum, sat'n, %	105	110

Other operating conditions for the two runs were the same. Sulfite oxidation of 30 percent for Run 583-2B was relatively high because of air leakage. However, oxidation was even higher for Run 591-2A at 43 percent without air leakage into the downcomer. This may be partially due to the low inlet SO_2 concentration of 2300 ppm (high O_2/SO_2 ratio in the inlet flue gas). The scrubber inlet liquor gypsum saturation was about the same in both runs. However, gypsum scaling was observed in Run 583-2B but not Run 591-2A.

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* Effective magnesium ion concentration is defined as the total magnesium ion minus that magnesium ion concentration equivalent to total chlorides. Magnesium chloride has no effect on SO_2 removal.

Runs 592-2A and 594-2A were made under the same operating conditions, except for the difference in the downcomer used. These runs are compared below with Run 584-2A, made in 1976 (Reference 4).

	592-2A	594-2A	584-2A
EHT residence time, min	4.1	4.1	4.1
EHT level, ft	17	17	17
Downcomer to EHT	Ext.	Int.	Int.
Air leakage	No	No	No
Percent SO_2 removal	95	93	94
Inlet SO_2 concentration, ppm	2850	2850	2950
SO_2 make-per-pass, m-moles/liter	13.8	13.8	15.0
Percent sulfite oxidation	25	18	20
TCA inlet liquor gypsum sat'n, %	105	90	50

Operating conditions for Runs 594-2A and 584-2A were essentially the same. Inlet SO_2 concentrations and SO_2 removals were about the same for all three runs. Gypsum saturation during Run 584-2A was only 50 percent, compared with about 100 percent for Runs 592-2A and 594-2A. All three runs were free of gypsum scaling.

In general, MgO addition improved the SO_2 removal efficiency, but no correlation appeared to exist between gypsum saturation and SO_2 make-per-pass. Lower sulfite oxidation tended to give lower gypsum saturation.

16.1.3 Effect of Slurry Flow Rate

Run 593-2A was made at a reduced slurry flow rate of 900 gpm. The slurry level in the hold tank was lowered from 17 to 12.8 ft to maintain the same residence time at 4.1 minutes. SO_2 removal was not significantly affected by the reduced liquid-to-gas ratio and remained high at 93 percent with 2850 ppm inlet SO_2 concentration. As a result, SO_2 make-per-pass increased to 18.8 m-moles/liter.

Run 593-2A is compared below with Run 585-2A, made in 1976.

	593-2A	585-2A
EHT residence time, min	4.1	4.1
EHT level, ft	12.8	12.8
Downcomer to EHT	Ext.	Int.
Air leakage	No	Yes
Percent SO_2 removal	93	85
Inlet SO_2 concentration, ppm	2850	2900
SO_2 make-per-pass, m-moles/liter	18.8	17.5
Percent sulfite oxidation	24	28
TCA inlet liquor gypsum sat'n, %	85	105
TCA inlet liquor sulfite conc., ppm	4855	4190

The conditions for the two runs were essentially the same, except for the difference in the downcomer used. Air leakage into the downcomer occurred in Run 585-2A, giving higher sulfite oxidation and gypsum saturation. The higher SO_2 removal for Run 593-2A may be attributed to the lower oxidation and higher sulfite concentration. Slight gypsum scaling occurred during both runs. It appeared that the gypsum scaling potential is higher at higher SO_2 make-per-pass.

16.2 SUMMARY OF FINDINGS

Six test runs were made on the TCA system with limestone slurry and with flue gas containing high fly ash loading. Of the six runs, two were made without MgO addition, one with 5000 ppm effective Mg^{++} concentration, and the other three with 9000 ppm effective Mg^{++} concentration. These runs were made to resolve some inconsistent results from earlier limestone/MgO tests (made in 1976) in which air leakage into the scrubber downcomer was suspected during some runs, causing higher than normal sulfite oxidation and gypsum scaling. Unfortunately, the inconsistent results obtained in 1976 were not resolved because of the wide variations in the inlet SO_2 concentration mentioned earlier. The following is a summary of findings.

- Higher effective Mg^{++} concentration is required in a limestone system than in a lime system to obtain a similar degree of improvement in SO_2 removal efficiency. This is probably due to the lower pH (5 to 6) inherent in the limestone system, where the sulfite-bisulfite equilibrium favors a shift toward bisulfite, which is not an SO_2 scrubbing species.
- Under typical operating conditions, SO_2 removal improved by about 15 percentage points with 9000 ppm effective Mg^{++} concentration.
- Adding MgO at the levels tested did not always result in gypsum subsaturated operation. Lower sulfite oxidation tended to give lower gypsum saturation.
- No correlation appeared to exist between gypsum saturation and SO_2 make-per-pass. However, gypsum scaling potential tended to be higher (incipient scaling gypsum saturation level tended to be lower) at higher SO_2 make-per-pass.

Section 17

TCA LIME/MgO TEST RESULTS

Lime testing with MgO addition was conducted from early February through late June 1978. These tests were made in the same period as the limestone testing with magnesium oxide addition reported in Section 16.

As with the limestone/MgO tests, the main purpose of the lime/MgO tests was to resolve the inconsistent results among the earlier tests (Runs 601-2A through 617-2A) made in 1976. In some of those earlier lime/MgO tests, air leakage into the scrubber downcomer caused higher than normal sulfite oxidation, and gypsum scaling was observed (see Sections 10 and 11, Reference 4).

The reason for air leakage in those earlier tests and the remedy to prevent the air leakage for the runs reported in this section have been presented in Section 16. The corrective action involved the installation of a scrubber downcomer external to the effluent hold tank near the tank bottom to ensure proper vacuum seal.

17.1 DISCUSSIONS OF TEST RUN RESULTS

Nine lime runs were made from early February through late June 1978. These were two base case lime runs without MgO addition and seven lime runs with

2000 ppm effective Mg^{++} concentration.* Flue gas having high fly ash loadings was used in each run. Major test conditions and important test results are summarized in Table 17-1. Additional detailed information for these runs are given in Appendices B through D, and H through J.

As has been mentioned in Section 16, coals from different sources were burned in Boiler No. 10 during the coal miners' strike in the first quarter of 1978. Inlet SO_2 concentration fluctuated as much as tenfold (320 to 3400 ppm), and the run-average concentrations were significantly lower than normal during most of the runs. The wide variations in inlet SO_2 concentration created process control problems and caused difficulties in the data interpretation and in the run-to-run comparison of test results.

17.1.1 Base Case Runs 618-2A and 618-2B

Runs 618-2A and 618-2B were base case runs without MgO addition. These runs were compared with the subsequent lime/MgO runs to observe the effect of magnesium ion. Run 618-2A was made with the internal downcomer. The scrubber effluent was later routed to the external downcomer (Run 618-2B) when the frozen slurry in the external downcomer was thawed (see Subsection 16.1.1).

Sulfite oxidations and percent SO_2 removals for these runs were relatively high because of the low inlet SO_2 concentrations.

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* Effective magnesium ion concentration is defined as the total magnesium ion minus that magnesium ion concentration equivalent to total chlorides. Magnesium chloride has no effect on SO_2 removal.

Table 17-1

SUMMARY OF LIME TESTS WITH MgO ADDITION ON THE TCA SYSTEM

Major Test Conditions(1)	618-2A	618-2B	619-2A	620-2A	621-2A	622-2A	622-2B	623-2A	624-2A
MgO addition	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Fly ash loading	High	High	High	High	High	High	High	High	High
Gas rate, acfm @ 300°F	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000
Slurry flow rate to TCA, gpm	1200	1200	1200	900	1200	900	900	1200	900
Percent solids recirculated	8	8	8	8	8	8	8	8	8
EHT residence time, min(2)	4.1	4.1	4.1	4.1	3.0	4.1	4.1	3.0	3.0
EHT level, ft(2)	17	17	17	12.8	12.5	12.8	12.8	12.5	9.4
Downcomer to EHT(2)	Int.	Ext.	Ext.	Ext.	Ext.	Ext.	Ext.	Ext.	Ext.
TCA inlet pH (controlled)	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
Lime addition point(3)	DC	DC	DC	DC	DC	EHT	DC	DC	DC
Effective Mg^{++} concentration, ppm	0	0	2000	2000	2000	2000	2000	2000	2000
Selected Results									
Percent SO_2 removal	90	96	94	91	96	92	85	91	82
Inlet SO_2 concentration, ppm	2100	1900	1850	1600	1950	2600	2600	2550	2900
SO_2 make-per-pass, m-moles/liter	10.2	8.9	9.2	10.3	10.3	16.4	15.0	12.3	16.4
TCA inlet liquor sulfite concentration, ppm(4)	85	80	355	330	310	940(5)	465	410	480
TCA inlet liquor gypsum saturation, %	120	120	90	95	105	95	95	70	65
Percent sulfite oxidation	28	30	23	27	29	22	14	14	15
Percent lime utilization	93	94	98	97	98	99	96	94	99
Effective Mg^{++} concentration, ppm	0	0	2360	2090	2135	4510(5)	2150	2190	1950
Onstream hours	162	88	306	106	239	91	125	271	269

Notes:

(1) All runs were made with 3 beds (4 grids) and with nominally 5 inches/bed of 1-5/8 inch diameter nitrile foam spheres. Clarifier and centrifuge were used for solids dewatering in all runs except Run 624-2A in which clarifier only was used.
(2) The effluent hold tank (D-204) was 7 ft in diameter and 21 ft high. Tests were made with either an internal or external downcomer.
(3) EHT or downcomer(DC).
(4) Total sulfite includes $SO_3^=$ and HSO_3^-.
(5) Steady-state concentrations were not reached for Run 622-2A from a previous high magnesium limestone run.

17.1.2 Effect of MgO Addition

In Run 619-2A, MgO was added to maintain 2000 ppm effective Mg^{++} concentration in the slurry liquor. Other test conditions for the run were the same as Run 618-2B. Due to the low inlet SO_2 concentrations of about 1900 ppm for both Runs 618-2B and 619-2A, the expected improvement in SO_2 removal with 2000 ppm effective Mg^{++} concentration was not discernible. The SO_2 removal of 96 percent for Run 618-2B was already high at the low inlet SO_2 concentration without MgO addition. Run 619-2A showed only a slight increase in SO_2 make-per-pass from 8.9 to 9.2 m-moles/liter. A possible explanation might be that the gas phase mass transfer resistance became significant in both runs at the low inlet SO_2 concentration, and that the increased mass transfer and reaction rates in the liquid phase due to magnesium ion did not significantly improve the overall rate.

Run 619-2A is compared below with Run 601-2A, which was made in 1976 (Reference 4) under identical operating conditions except that the latter had the internal downcomer:

	619-2A	601-2A
Downcomer to EHT	Ext.	Int.
Air leakage	No	No
Percent SO_2 removal	94	92
Inlet SO_2 concentration, ppm	1850	2900
SO_2 make-per-pass, m-moles/liter	9.2	13.5
Percent sulfite oxidation	23	14
TCA inlet liquor gypsum sat'n, %	90	50
TCA inlet liquor sulfite conc., ppm	355	525

Sulfite oxidation and gypsum saturation for Run 601-2A were much lower than for Run 619-2A. The rate of SO_2 removal was much higher for Run 601-2A, as evidenced by the higher SO_2 make-per-pass and liquor sulfite concentration.

17.1.3 Effect of Downcomer Air Leakage

Runs 620-2A and 621-2A were conducted to compare with Runs 604-2A and 613-2A respectively, which were made in 1976 (Reference 4). Air leakage into the internal downcomer was suspected in Runs 604-2A and 613-2A of causing high sulfite oxidation and gypsum scaling. The results of these four runs are compared in pairs, as follows:

	620-2A	604-2A	621-2A	613-2A
Slurry Flow Rate, gpm	900	900	1200	1200
EHT residence time, min	4.1	4.1	3.0	3.0
EHT level, ft	12.8	12.8	12.5	12.5
Downcomer to EHT	Ext.	Int.	Ext.	Int.
Air leakage	No	Yes	No	Yes
Percent SO_2 removal	91	73	96	85
Inlet SO_2 concentration, ppm	1600	3200	1950	3050
SO_2 make-per-pass, m-moles/liter	10.3	17.5	10.3	14.0
Percent sulfite oxidation	27	28	29	35
TCA inlet liquor gypsum sat'n, %	95	90	105	95

Because of air leakage into the internal downcomer, sulfite oxidation in Runs 604-2A and 613-2A was higher than normal (28 and 35 percent, respectively). Unfortunately, oxidation for Runs 620-2A and 621-2A was also high (27 and 29 percent, respectively), because of the low inlet SO_2 concentrations (high O_2/SO_2 ratio in inlet flue gas). Gypsum saturations in all four runs were similar (about 95 percent). However, gypsum scaling occurred in Runs 604-2A and 613-2A but not in Runs 620-2A and 621-2A. Therefore, as with limestone/MgO tests, higher SO_2 make-per-pass increases the gypsum scaling potential.

17.1.4 Effect of Inlet SO_2 Concentration

Runs 622-2A, 622-2B, and 623-2A were conducted to replicate Runs 620-2A and

621-2A operating conditions, but at a normal inlet SO_2 concentration of about 2600 ppm.

Run 622-2A was intended to replicate Run 620-2A, but the fresh lime slurry was inadvertently added to the effluent hold tank rather than the external downcomer. In addition, magnesium concentration did not reach a steady-state level during Run 622-2A from a previous high-magnesium limestone run. Therefore, a comparison between those two runs would be irrelevant.

As can be seen in Table 17-1, direct comparisons are possible between Runs 620-2A and 622-2B and between Runs 621-2A and 623-2A to study the effect of inlet SO_2 concentration. Average sulfite oxidation was about 28 percent at 1600 to 1950 ppm average inlet SO_2 concentrations; sulfite oxidation was only one-half as great (14 percent) when the inlet SO_2 increased to about 2600 ppm. Gypsum saturation was lower (70 to 95 percent) at the lower sulfite oxidation, compared with about 100 percent saturation at the higher oxidation. SO_2 removal was about 5 percentage points lower at the higher inlet SO_2 concentration, as expected. However, SO_2 make-per-pass was 20 to 50 percent higher at the higher inlet SO_2 concentration.

17.1.5 Effects of Hold Tank Residence Time and Slurry Flow Rate

Run 624-2A was originally designed to be compared with Run 620-2A for the purpose of observing the effect of the hold tank residence time on sulfite oxidation and gypsum saturation. However, because of the large difference in the inlet SO_2 concentrations, direct comparison of these two runs would not be meaningful.

Referring to Table 17-1, Run 624-2A can be compared with Run 622-2B for the effect of hold tank residence time, and with Run 623-2A for the effect of slurry flow rate (liquid-to-gas ratio). These three runs had much closer inlet SO_2 concentrations. Sulfite oxidations for all three runs were about the same (14 to 15 percent).

Dropping the residence time from 4.1 minutes (Run 622-2B) to 3.0 minutes (Run 624-2A) reduced the gypsum saturation from 95 to 65 percent. Reducing the slurry flow rate from 1200 gpm (Run 623-2A) to 900 gpm (Run 624-2A) while keeping the residence time unchanged did not significantly change the gypsum saturation. Percent SO_2 removal decreased, as expected, from 91 percent at an inlet SO_2 concentration of 2550 ppm to 82 percent at an inlet concentration 2900 ppm. SO_2 make-per-pass increased from 12.3 to 16.4 m-moles/liter because of the reduced liquid-to-gas ratio from 50 to 37 gal/Mcf.

17.2 SUMMARY OF FINDINGS

Nine runs were made on the TCA system with lime slurry and with flue gas having high fly ash loading. Of the nine runs, two were made without MgO addition as base cases, and seven were made with 2000 ppm effective Mg^{++} concentration. As with the limestone/MgO tests (Section 16), the lime/MgO tests were conducted to resolve inconsistent results among earlier tests made in 1976. In those earlier tests, air leakage into the scrubber downcomer during some runs caused high sulfite oxidation and gypsum scaling. Unfortunately, in most of the runs reported in this section, high sulfite oxidation was also encountered. This high oxidation was due to lower than normal inlet SO_2 concentrations, and the inconsistent results obtained in 1976 were not resolved. However, because of low SO_2 make-per-pass, gypsum scaling did not occur. The following findings reflect results of the recent tests:

- At low inlet SO_2 concentrations (about 1600 to 2000 ppm), improvement in SO_2 removal was not discernible with 2000 ppm effective Mg^{++} concentration. Overall reaction rate may be controlled by the gas phase mass transfer at the low inlet SO_2 concentrations.
- The lower inlet SO_2 concentrations (about 1600 to 2000 ppm) resulted in sulfite oxidations 10 to 15 percentage points higher than normal, probably because of the higher O_2/SO_2 ratio in the inlet flue gas. Higher oxidation would also render magnesium ion ineffective in SO_2 removal enhancement.
- As in the limestone/MgO tests, lower sulfite oxidation tended to yield lower gypsum saturation. No correlation appeared to exist between gypsum saturation and SO_2 make-per-pass. At similar gypsum saturation levels, gypsum scaling potential appeared to be higher at higher SO_2 make-per-pass. (Incipient scaling percent gypsum saturation tended to be lower at higher SO_2 make-per-pass.)
- Within the range of the hold tank residence time tested (3.0 to 4.1 minutes), lower residence time resulted in lower gypsum saturation at similar sulfite oxidation level (Run 622-2B versus 624-2A).

Section 18

FLUE GAS CHARACTERIZATION

18.1 SPECIAL TEST RUNS

An intensive testing period to explore the effect of major operating variables on each system has been completed. Tests completed on the TCA and one test on the venturi/spray tower are reported in this section. Previous venturi/spray tower tests were reported in the Third Progress Report (Reference 4). For a detailed discussion of the tests, the reader is referred to Reference 9.

18.1.1 Test Program

The test series on both the venturi/spray tower and TCA systems was designed to determine the effect of major operating variables on particulate mass removal and size distribution.

Variables investigated in the venturi/spray tower system were flue gas rate, slurry rate, MgO addition, venturi pressure drop, mist eliminator configuration, and percent solids recirculated. Variables investigated in the TCA system were flue gas rate, slurry rate, MgO addition, and mist elimination wash scheme.

The mist eliminators on both systems were washed intermittently on top with fresh water (8-hour sequential cycle with one of the six nozzles activated for 4 minutes every 80 minutes). The following three modes of bottom wash were evaluated:

- High-frequency intermittent fresh water (HI), 4 min/hr at 1.5 gpm/ft^2, shut off during testing
- Low-frequency intermittent fresh water (LI), 6 min/4 hr at 1.5 gpm/ft^2, shut off during testing
- Continuous diluted clarified liquor (C), at 0.4 gpm/ft^2, left on during testing

For one run on each system, flue gas to the scrubber was obtained downstream of the electrostatic precipitator (ESP) to evaluate scrubber performance using flue gas with low fly ash loading. Flue gas for all the other runs came from a takeoff just downstream of the boiler air preheaters. Listed in Table 18-1 are the run conditions for the TCA system tests, and in Table 18-2, the conditions for the venturi/spray tower system tests.

18.1.2 Sampling Locations

Samples were taken from both the inlet and outlet of each scrubber. The duct at these locations was forty inches in diameter. Two eight-point traverses, 90° apart, were performed for each mass loading and size distribution test. The inlet sample ports were located upstream of the scrubber inlet where the gas temperature was approximately 300 to 330°F. The outlet sample port was located after the reheater at the scrubber outlet where the gas temperature was approximately 250°F. The sample ports were about two duct diameters upstream and six duct diameters downstream of the nearest obstruction.

18.1.3 Test Methods

The procedure used for measuring particulate mass loading was a modification of EPA Method Five. A Hi-Volume sampling train manufactured by the Aerotherm

Table 18-1

FLUE GAS CHARACTERIZATION PROGRAM RESULTS FOR THE TCA SYSTEM

Controlled Variables	TFG-2A	TFG-2B	TFG-2C	TFG-2D	TFG-2E	TFG-2F	706-2A
Gas Rate, acfm @ 300°F	30,000	30,000	30,000	20,000	30,000	30,000	30,000
Scrubber Gas Velocity, ft/sec	12.5	12.5	12.5	8.4	12.5	12.5	12.5
Slurry Rate, gpm	1200	1200	1200	1200	600	1200	1200
Percent Solids Recirculated	15	15	15	15	15	15	15
Fly Ash Loading	High	High	High	High	High	High	Low
Alkali	Limestone	Limestone	Limestone	Limestone	Limestone	Limestone	Limestone
Mist Eliminator Configuration	chevron	chevron	chevron	chevron	chevron	chevron	chevron
Mist Eliminator Wash Scheme (1)	HI	HI	C	C	C	no wash	HI
MgO Addition	Yes	No	No	No	No	No	No
Uncontrolled Variables							
Gas Velocity at Mist. Elim., ft/sec	8.2	8.2	8.2	5.5	8.2	8.2	8.2
TCA Beds ΔP Range, in. H_2O	5.6 - 7.4	7.0 - 9.0	7.0 - 8.5	4.4 - 5.1	4.4 - 5.0	5.6 - 7.2	8.0 - 10.0
Mist Eliminator ΔP Range, in. H_2O	0.47 - 0.50	0.45 - 0.60	0.48 - 0.60	0.18 - 0.20	0.45 - 0.55	0.44 - 0.50	0.40 - 0.60
Total Dissolved Solids, ppm	50,000 - 55,000	7,300 - 9,500	5,000 - 10,000	5,700 - 7,400	4,600 - 6,300	6,400 - 8,700	7,000 - 9,000
Flue Gas Measurements							
Mass Loading, Inlet							
Average, gr/dscf	4.67	6.07	5.82	6.13	5.69	4.53	0.124
Range, gr/dscf	3.55 - 5.61	5.14 - 7.59	4.77 - 7.51	4.23 - 6.86	4.39 - 6.61	3.67 - 5.43	0.065 - 0.225
Mass Loading, Outlet							
Average, gr/dscf	0.055	0.048	0.064	0.056	0.065	0.042	0.026
Range, gr/dscf	0.034 - 0.092	0.037 - 0.058	0.058 - 0.080	0.051 - 0.065	0.054 - 0.088	0.035 - 0.046	0.018 - 0.032
Mass Loading Removal							
Average, %	98.8	99.2	98.9	99.1	98.8	99.1	74.0
Range, %	98.3 - 99.4	98.9 - 99.4	98.4 - 99.2	98.7 - 99.2	98.4 - 99.1	99.0 - 99.2	53.8 - 85.8
Test Philosophy	MgO addition.	Basic operating conditions. HI wash scheme.	Basic operating conditions. C wash scheme.	Low gas rate.	Low liquor rate.	Basic operating conditions. No wash.	Low inlet fly ash loading.
Comments	Noticeable scale particles were found on the outlet mass loading filter.						

(1) Wash Schemes: HI, high frequency fresh water bottom wash with the bottom wash off during testing; C, continuous diluted clarified liquor bottom wash left on during testing. With both schemes a low frequency fresh water top wash was used.

Table 18-2

FLUE GAS CHARACTERIZATION PROGRAM RESULTS FOR THE VENTURI/SPRAY TOWER SYSTEM

Controlled Variables	VFG-1A	VFG-1B		VFG-1C	VFG-1D	VFG-1E	VFG-1F	VFG-1G	VFG-1I	VFG-1P	VFG-1Q
Gas Rate, acfm @ 330°F	35,000	35,000	35,000	35,000	20,000	35,000	35,000	35,000	35,000	35,000	35,000
ST Gas Velocity, ft/sec	9.4	9.4	9.4	9.4	5.4	9.4	9.4	9.4	9.4	9.4	9.4
ST Slurry Rate, gpm	1,400	1,400	1,400	1,400	1,400	1,400	0	1,400	1,400	1,400	1,400
Venturi Slurry Rate, gpm	600	600	600	600	600	375	600	600	600	140	--
Venturi ΔP, in. H_2O	9	9	9	9	9	4.5 - 6.0	9	9	9	2.8 - 3.2	2.5
Percent Solids Recirculated	8	8	8	8	8	8	8	8	15	8	8
Fly Ash Loading	High	Low	Low	High	High	High	High	High	High	High	Low
Alkali	Lime	Lime	Lime	Lime	Lime	Lime	Lime	Lime	Lime	Lime	Lime
Mist Elim. Configuration	chevron	chevron	chevron	chevron	chevron	chevron	chevron	chevron + York	chevron	chevron	chevron
Mist Elim. Wash Scheme[(1)]	LI	LI	LI	LI	LI	LI	LI	LI	LI	LI	LI
MgO Addition	Yes	No	No	No	No	No	No	No	No	No	No
Uncontrolled Variables											
Gas Vel. at Mist Elim., ft/sec	9.4	9.4	9.4	9.4	5.4	9.4	9.4	9.4	9.4	9.4	9.4
System ΔP Range, in. H_2O	13.3 - 13.8	13.1 - 13.8	13.6 - 14.0	13.7 - 14.3	10.2 - 10.8	9.5 - 10.5	12.5 - 13.2	14.1 - 15.5	13.7 - 14.3	6.1 - 9.7	7.2 - 7.9
Total Dissolved Solids, ppm	13,200 - 18,000	2,500 - 5,200	7,000 - 9,500	7,700 - 9,600	6,000 - 8,800	5,400 - 8,000	7,200 - 10,000	8,300 - 9,400	6,600 - 9,000	6,900 - 8,100	1,000 - 1,660
Flue Gas Measurements											
Mass Loading Inlet											
Average, grains/dry scf	4.41	0.070	0.367	6.17	4.53	5.11	5.14	6.05	5.18	5.63	0.148
Range, grains/dry scf	3.66 - 5.50	0.039 - 0.096	0.118 - 0.609	4.82 - 8.39	3.68 - 5.78	3.77 - 7.90	3.72 - 6.41	3.90 - 8.76	3.70 - 6.06	5.13 - 6.66	0.102 - 0.195
Mass Loading Outlet											
Average, grains/dry scf	0.032	0.005	0.005	0.019	0.026	0.028	0.027	0.021	0.026	0.036	0.020
Range, grains/dry scf	0.023 - 0.046	0.003 - 0.007	0.003 - 0.009	0.013 - 0.023	0.018 - 0.039	0.020 - 0.037	0.022 - 0.037	0.018 - 0.024	0.017 - 0.037	0.031 - 0.040	0.016 - 0.023
Mass Loading Removal											
Average, %	99.3	92.0	98.3	99.7	99.4	99.4	99.5	99.6	99.5	99.4	86.4
Range, %	99.0 - 99.4	82.1 - 96.3	99.5 - 99.3	99.5 - 99.8	99.1 - 99.6	99.1 - 99.7	99.4 - 99.6	99.4 - 99.8	99.4 - 99.7	99.3 - 99.5	79.6 - 90.7
SO_3 Inlet											
Average, ppm	10.9	2.6	5.4	8.9	9.3	15.4	2.1	8.9	10.7	6.0	--
Range, ppm	3.4 - 14.8	1.7 - 3.7	3.6 - 7.2	3.0 - 17.1	4.5 - 13.5	7.1 - 24.8	0.4 - 4.5	2.5 - 15.8	5.8 - 21.2	4.1 - 7.8	--
SO_3 Outlet											
Average, ppm	2.9	0.9	2.7	3.6	4.1	8.9	0.3	4.1	3.5	1.7	--
Range, ppm	0.1 - 5.2	0.5 - 1.5	1.6 - 4.1	0.3 - 8.3	0.4 - 7.6	3.2 - 13.9	0.0 - 0.9	2.8 - 5.3	0.5 - 10.9	1.1 - 2.3	--
SO_3 Removal											
Average, %	74.9	67.3	50.9	62.2	53.9	--	71.0	66.9	72.5	64.9	--
Range, %	54.9 - 99.2	47.1 - 81.5	39.3 - 64.3	27.2 - 97.1	37.5 - 65.5	--	25.0 - 100.0	66.7 - 67.1	46.8 - 91.4	43.9 - 85.9	--
Test Philosophy	MgO add'n.	Low inlet fly ash loading.		Basic operating conditions.	Low gas rate.	Minimum venturi.	Venturi only.	Basic operating conditions. York demister added.	High percent solids recirculated.	Repeat of Run VFG-1E at correct conditions.	Spray tower only with low inlet Fly Ash Loading.
Comments		TDS low due to non-equilibration of clarifier.	TDS raised by $CaCl_2$ add'n. Boiler upset conditions caused higher inlet grain loading.			Flowmeter probs caused high flow to venturi. Desired 140 gpm. SO_3 values not simultaneous due to equip probs, no removals calculated.		Demister plugged after 55 hrs. of operation.			40 gpm water used upstream of venturi to protect rubber lining.

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(1) LI represents a low frequency, fresh water, top and bottom mist eliminator wash scheme. The bottom wash was shut off during testing.

Division of Acurex Corporation was used. The major differences in test conditions between sampling at Shawnee and a typical Method Five application were: (1) increased sampling flow rate (2 cfm versus 0.75 cfm, typical for EPA Method Five) (2) filter temperatures in the 350°F to 400°F range to prevent acid (SO_3) condensation, and (3) the first two impingers filled with Na_2CO_3 solution to remove SO_2 and to provide corrosion protection for the pump and dry gas meter.

Particulate size distributions were measured with out-of-stack heated inertial impactors. A Brink Model BMS-11 impactor was used for inlet sampling and a Meteorology Research Inc. (MRI) Model 1502 impactor was used for outlet sampling.

To obtain representative size distribution measurements, sampling traverses were made. The flow rate through the impactor was held constant to ensure consistent impactor stage cut sizes. The sampling nozzle was chosen to provide average duct velocity at the nozzle inlet. Because of the uniformity of the duct velocity profile, isokinetic sampling rate was maintained within ± 10 percent by sampling at the average duct velocity.

Because all size distribution measurements were taken outside of the stack to facilitate temperature control, a fraction of the particulate was deposited in the probe and nozzle. For the outlet size distributions, the estimated probe fallout included a significant fraction of the particulate in the size range of the first three stages. Thus, it was necessary to combine the probe wash and the first three stages when computing grain loadings as a function of particle size. For the inlet measurements, no correction was required.

18.1.4 Results of Tests on the TCA System

Table 18-1 gives the results of the mass loading tests conducted on the TCA system. The average outlet mass loading ranged from 0.042 to 0.065 grain/dry scf for the high inlet fly ash loading tests and was 0.026 grain/dry scf for the test with low fly ash loading.

The average scrubber outlet emission values with high inlet fly ash loading were in the range of, and sometimes exceeded, the EPA New Source Performance Standards for particulate emissions. Preliminary results of mass loading versus opacity measurements indicated that removals in the 0.020 to 0.025 grain/dry scf range would be required to meet the EPA opacity standard for a 500-MW plant with a single stack (assuming a 70 ft/sec exit velocity). This value is well below the mass emission requirements.

Nondispersive infrared and thermogravimetric analysis of the particulate on a single outlet filter from the run with low fly ash loading indicated that emissions from entrained scrubber reaction products were around 0.005 grain/dry scf. On the basis of this single analysis, the outlet loadings appeared to be predominately fly ash. This was confirmed by the preliminary results from air/slurry entrainment tests on the TCA system which indicated a slurry (40 percent fly ash and 60 percent slurry reaction products) entrainment value between 0.003 and 0.005 grain/dry scf. This value is in agreement with the low reaction product emission value and supports the conclusion that over 90 percent of the TCA emission is fly ash.

The highest emission values experienced under base case conditions occurred with a continuous diluted clarified liquor mist eliminator underwash (Run

TFG-2C, 0.064 grain/dry scf outlet). Changing to an all fresh-water mist eliminator wash scheme (Run TFG-2B, 0.048 grain/dry scf outlet) reduced emissions.

Reducing the circulating slurry rate had no effect on the emissions (Run TFG-2E, 0.065 grain/dry scf outlet), but reducing the gas rate (Run TFG-2D, 0.056 grain/dry scf outlet) tended to reduce the emissions. MgO addition (Run TFG-2A, 0.055 grain/dry scf outlet) tended to increase emissions, although this run did not have the highest emission rate since it used a fresh-water mist eliminator wash scheme.

Inlet and outlet grain loadings as a function of aerodynamic particle size were calculated using mean values of the measurements for each run. These loadings are plotted in Figure 18-1 for runs with high fly ash loading and in Figure 18-2 for runs with low fly ash loading. The inlet distributions were similar to the venturi/spray tower measurements, confirming that both scrubber inlet size distributions were the same even though they were taken from different sides of the boiler outlet duct.

Mass penetration as a function of aerodynamic particle size is plotted in Figure 18-3 for runs with high inlet fly ash loading and in Figure 18-4 for runs with low inlet fly ash loading. The mass penetration for the high fly ash loading runs varied from about 20 to 90 percent for 0.1-micron particles and less than 4 percent for particles larger than 5 microns. For runs with low fly ash loading, penetration was between 25 and 70 percent for 0.1-micron particles and about 6 percent for particles larger than 5 microns.

For runs with high fly ash loading, emission of particles smaller than 2 microns actual diameter averaged 0.025 grain/dry scf, except for the run

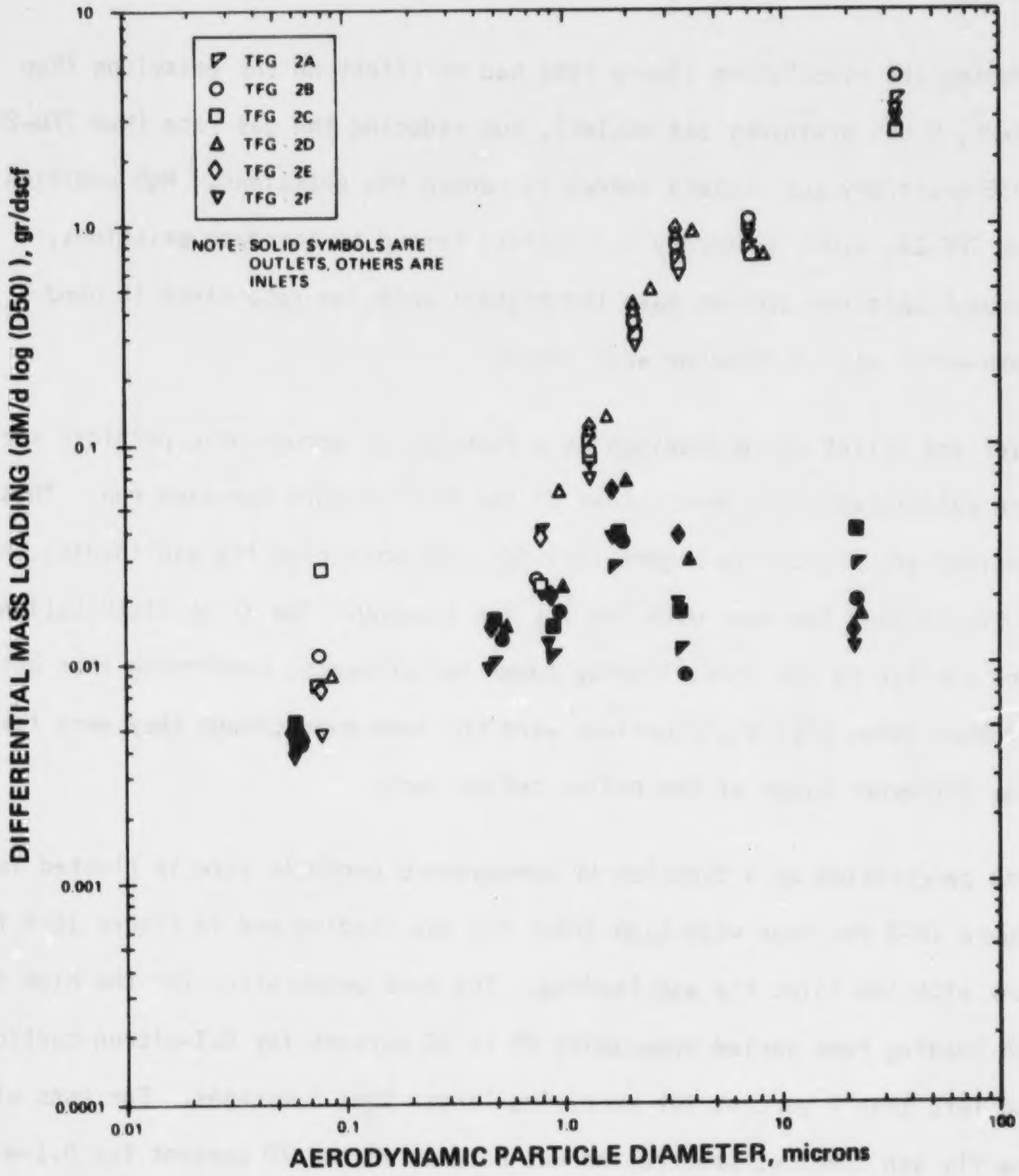

Figure 18-1. Mean Differential Mass Loading Versus Aerodynamic Particle Size for all TCA System High Fly Ash Loading Runs

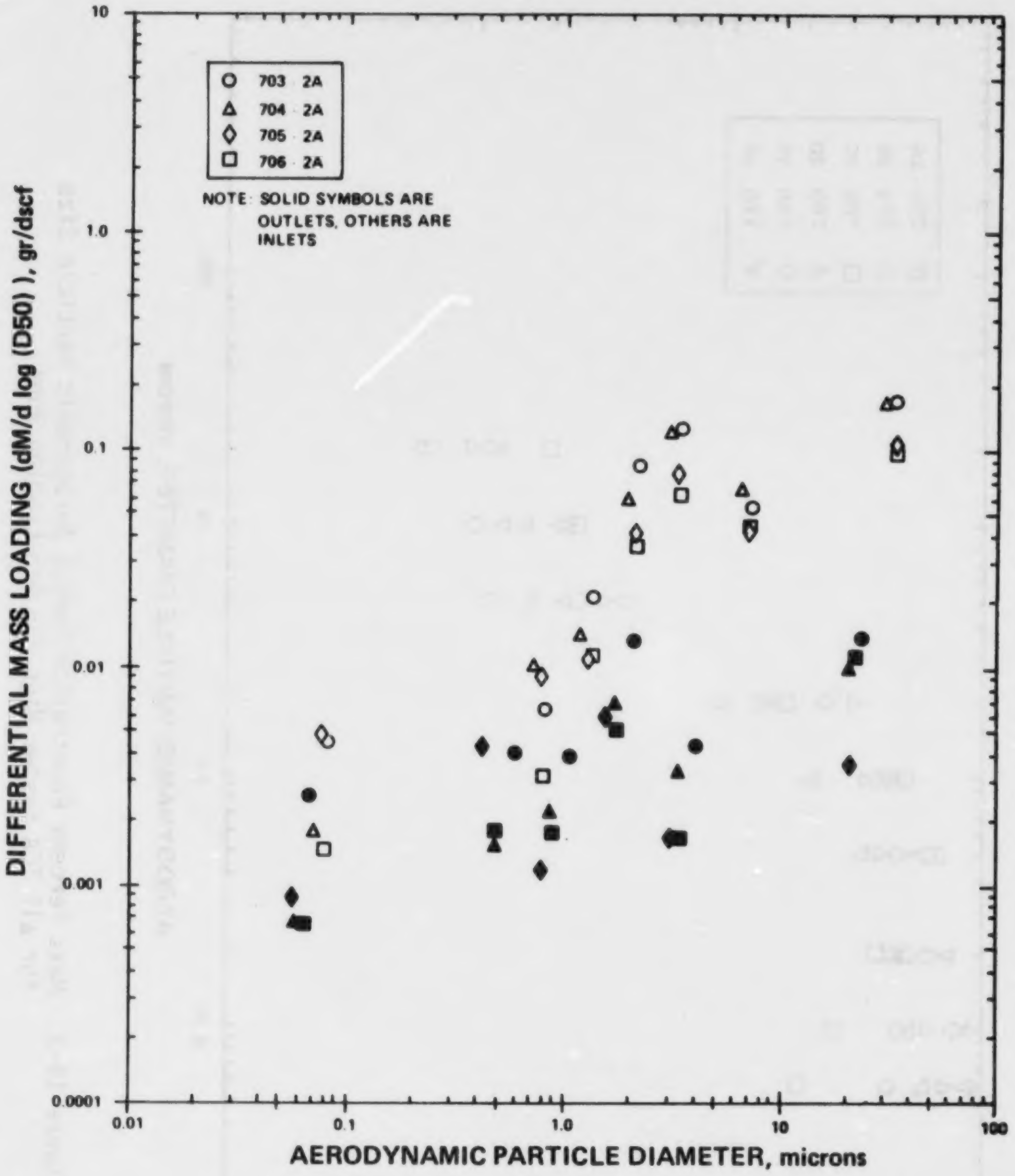

Figure 18-2. Mean Differential Mass Loading Versus Aerodynamic Particle Size for all TCA System Low Fly Ash Loading Runs

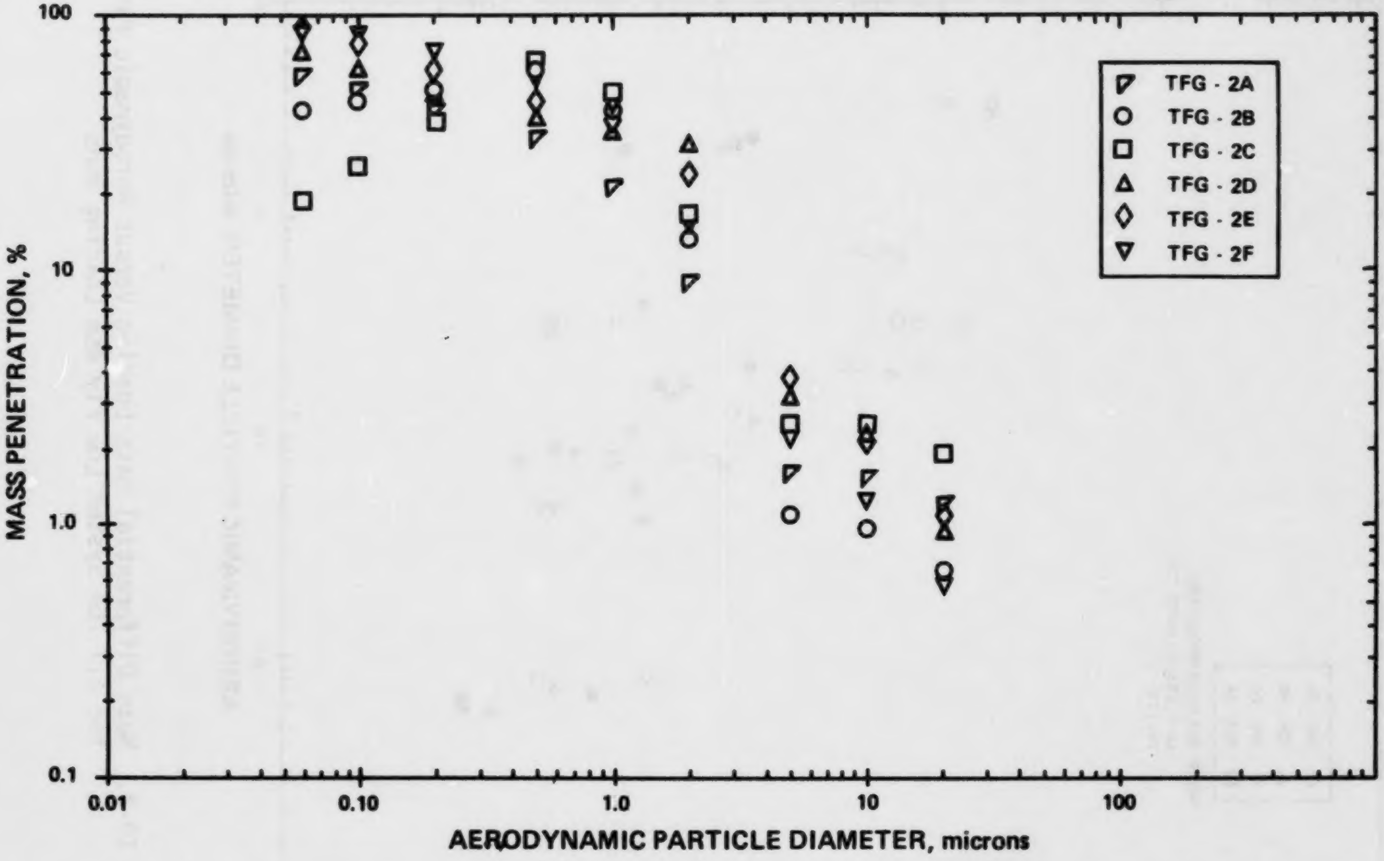

Figure 18-3. Mass Percent Penetration Versus Aerodynamic Particle Size for all TCA System High Fly Ash Loading Runs

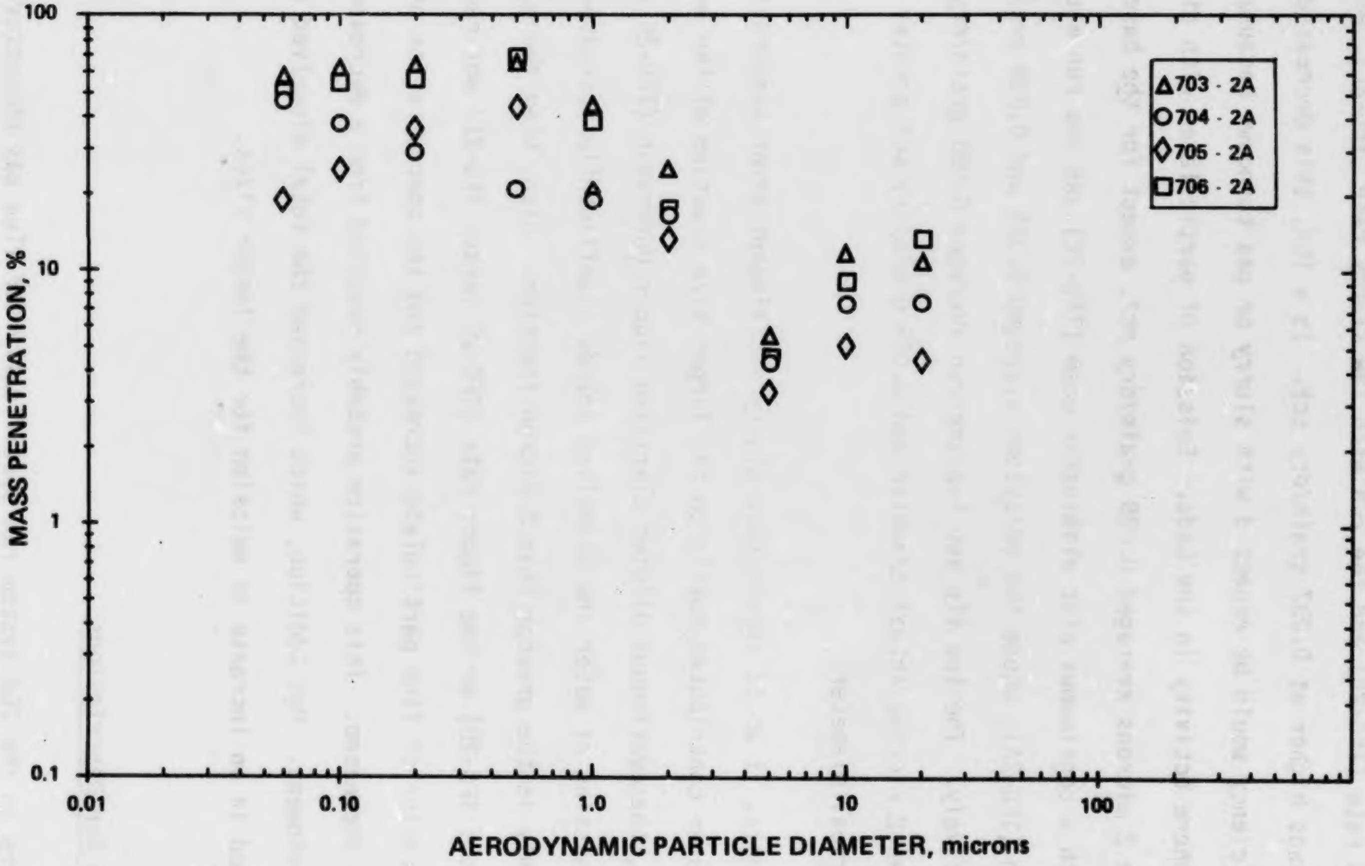

Figure 18-4. Mass Percent Penetration Versus Aerodynamic Particle Size for all TCA Low Fly Ash Loading Runs

with low gas rate (TFG-2D) and the run with low slurry rate (TFG-2E), where the average was higher at 0.037 grain/dry scf. In a TCA, this decreased removal efficiency would be expected with slurry or gas turndown because of decreased sphere activity in the beds. Emission of particulates with diameters greater than 2 microns averaged 0.028 grain/dry scf, except for the base case run with a continuous mist eliminator wash (TFG-2C) and the run with MgO addition (TFG-2A), where the emissions averaged 0.055 and 0.038 grain/dry scf, respectively. The low fly ash loading run averaged 0.003 grain/dry scf less than 2 microns actual diameter and 0.025 grain/dry scf greater than 2 microns actual diameter.

From these data, it would appear that slurry entrainment after evaporation in the reheater contributes mostly to the larger size fraction of the emissions. For example, the continuous diluted clarified liquor underwash (TFG-2C versus TFG-2B) consisting of water and dissolved solids significantly increased emissions only in the greater than 2 micron fraction. Also, when the gas rate (TFG-2C versus TFG-2D) or the liquor rate (TFG-2C versus TFG-2E) was reduced, the concentration of fine particulate increased and the concentration of larger particulate decreased. This operation probably resulted from a decrease in slurry entrainment. MgO addition, which increased the total dissolved solids, also resulted in an increase in emission for the larger sizes.

18.1.5 TCA Run Descriptions

All the tests on the TCA system run specifically for flue gas characterization data are described below.

Run TFG-2B began on February 4 and ended on February 10, 1977, after 128 operating hours. The run was the first in the series specifically designed to collect flue gas characterization data at typical operating conditions. The major test conditions and results are listed in Table 18-1. Flue gas data had also been collected during Run 706-2A and are included in Table 18-1 for comparison.

For Run TFG-2B, the average inlet grain loading was 6.07 grains/dry scf and the outlet was 0.048 grain/dry scf, a 99.2 percent removal.

Run TGF-2C began on February 10 and ended on February 14 after 93 hours of operation. Test conditions were the same as for Run TFG-2B except that the mist eliminator bottom wash scheme was changed from an intermittent wash with makeup water to a continuous wash with diluted clarified liquor. The purpose of the run was to observe the effect of this change on the outlet flue gas measurements. The average inlet grain loading was 5.82 grain/dry scf and the average outlet grain loading was 0.064 grain/dry scf, a 98.9 percent removal. The average outlet grain loading is higher than the previous Run TFG-2B.

Run TFG-2D began on February 15 and ended on February 19 after 93 operating hours. The purpose of the run was to observe the effect of reduced gas flow on flue gas measurements. Test conditions were the same as for Run TFG-2C, except that the gas rate was decreased from 30,000 acfm to 20,000 acfm. The average inlet grain loading was 6.13 grains/dry scf and the outlet grain loading was 0.056 grain/dry scf, a removal of 99.1 percent.

Run TFG-2E began on February 19 and ended on February 23 after 96 operating hours. The test conditions differed from those of Run TFG-2C in that the recirculating slurry rate was 600 gpm (cf. 1200 gpm for Run TFG-2C) and the effluent hold tank residence time was increased from 12 to 24 minutes. The average inlet grain loading was 5.69 grains/dry scf and the outlet grain loading was 0.065 grain/dry scf, a removal of 98.8 percent. This outlet grain loading is higher than in the previous run.

Run TFG-2F began on February 23 and ended on February 28 after 112 operating hours. The test conditions were identical to those for Run TFG-2C, except that both top and bottom mist eliminator washes were turned off when sampling the flue gas. The purpose of the test was to eliminate the effect of the mist eliminator washes on the flue gas measurements. The inlet grain loading averaged 4.53 grain/dry scf and outlet grain loading averaged 0.042 grain/dry scf, a removal of 99.1 percent. The outlet grain loading was 0.02 grain/dry scf less than Run TFG-2C which indicated, as expected, that continuous wash did contribute to the value.

Run TFG-2A began on February 28 and ended on March 3 after 76 hours of operation. Test conditions were the same as for Run TFG-2B except that MgO was added to maintain an effective liquor magnesium ion concentration of 9000 ppm. The purpose of the run was to observe the effect on the flue gas measurements of high concentration of dissolved solids in liquor. The inlet grain loading averaged 4.67 grain/dry scf and the outlet grain loading averaged 0.055 grain/dry scf, a removal of 98.8 percent. The outlet grain loading was not different from any of the previous runs, even with the large increase in total dissolved solids in the liquor. Noticeable numbers of scale particles were found on the outlet filter.

Run 706-2A began on January 14 and ended after 339 hours of operation on February 4. The test conditions were the same as those during Run TFG-2B except that flue gas with low fly ash loading was used. The average inlet grain loading was 0.124 grain/dry scf, and the average outlet grain loading was 0.026 grain/dry scf, a removal of only 74 percent.

18.1.6 Flue Gas Characterization - Run VFG-1Q

Run VFG-1Q, a flue gas characterization run, was made on the venturi/spray tower system. Previously unreported, this run was a continuation of the testing program for the venturi/spray tower. The results are listed in Table 18-2, which includes all the venturi/spray tower data for these tests.

Run VFG-1Q was conducted with the venturi plug wide open and without venturi flow. This was done in order to determine the particulate removal capability of the spray tower alone when operating on flue gas taken with low fly ash loading. Lime was used as SO_2 absorbent for this run.

To cool the flue gas and protect the spray tower rubber lining, about 40 gpm of water was used in the water sprays upstream of the venturi and in one of the four venturi tangential nozzles. The flue gas flow rate was 35,000 acfm (@ 300°F) and the slurry flow rate to the spray tower was 1400 gpm.

Inlet particulate mass loading averaged about 0.15 grain/dry scf. The particulate removal was higher than expected at about 85 percent. The venturi pressure drop averaged 2.5 inches H_2O and (corresponding to the venturi plug wide open) is believed to have significantly affected the particulate removal. However, there is no way to isolate the spray tower from the venturi to verify this assumption.

18.2 FLUE GAS MASS LOADING TESTS

The results of mass loading tests routinely performed during the reporting period on the venturi/spray tower and TCA systems are presented in Appendix M. The procedure used for measuring particulate mass loading was a modification of EPA Method Five described in Subsection 18.1.3.

In the venturi/spray tower, the outlet mass loading generally decreased as the pressure drop increased. For example, during Run 852-1A, the average outlet mass loading was 0.062 grain/dry scf with a system pressure drop of 3.3 inches H_2O. During Run 819-1A, the average outlet was 0.052 grain/dry scf with a pressure drop of 6.0 inches H_2O. During Run 863-1A the average outlet mass loading was 0.045 grain/dry scf with an average system pressure drop of 13.7 inches H_2O, and for Run 866-1A the outlet grain loading was 0.023 grain/dry scf with 16.7 inches H_2O pressure drop.

On several occasions, the venturi/spray tower slightly exceeded the EPA New Source Performance Standard for mass emissions from coal fired power plants (0.052 grain/dry scf assuming 30 percent excess air to the boiler).

The TCA showed the same relationship between the pressure drop and the outlet mass loading. For example, during Run 719-2A, when the pressure drop of the system averaged only 3.4 inches H_2O, the outlet mass loadings exceeded the performance standard during each test and the average grain loading was 0.060 grain/dry scf. In Run 619-2A, the average outlet grain loading was 0.044 grain/dry scf with an average pressure drop of 9.4 inches H_2O. In Run 618-2A, the outlet grain loading averaged 0.032 grain/dry scf with an average pressure drop of 12.4 inches H_2O.

The TCA exceeded the performance standard during several periods. In general, the standard was exceeded when the pressure drop was below about 8 inches H_2O.

18.3 AIR/SLURRY TEST RESULTS

During the April to May 1977 boiler outage, air/slurry tests were performed on both the venturi/spray tower and TCA systems in an attempt to better determine the effect of slurry entrainment on scrubber mass emissions. If air is substituted for flue gas in the scrubber, particulate emissions from the scrubber should result only from the entrained slurry. Unfortunately, the inlet air dust concentration was high (0.0006 to 0.0098 grain/dry scf) and oil from the oil-fired reheater was noted in the scrubber outlet probe wash during the TCA tests. Even after correcting for the presence of the oil, there was still no way to determine how much of the inlet dust had not been removed.

Thus, the only conclusion that can be drawn is that slurry-related mass emissions must be less than the measured outlet mass emissions. For the range of conditions tested, mass emissions of 0.001 to 0.003 grain/dry scf were measured for the venturi/spray tower system and 0.001 to 0.005 for the TCA system. The results of the tests for the TCA system and for the venturi/spray tower system are presented in Table 18-3 and 18-4, respectively.

18.3.1 Test Program

The test conditions are outlined in Table 18-5 for the TCA system and Table 18-6 for the venturi/spray tower system. The volumetric air flow rate was

Table 18-3
TCA SYSTEM AIR/SLURRY TEST RESULTS

Date	Run No.	Mass Loading, gr/dscf					Reheater Oil Valve % Open	Comment
		Inlet Total	Outlet					
			Total	Probe	Filter	Est.[1]		
4/7/77	TAS-2A*	--	0.0056	0.0013	0.0043	--	100	No known oil
4/7/77	TAS-2A*	--	0.0053	0.0007	0.0046	--	100	No known oil
4/7/77	TAS-2A*	--	0.0023	0.0003	0.0020	--	100	No known oil
4/8/77	TAS-2B	--	0.0086	0.0074	0.0012	0.001	100	Oil in probe wash
4/8/77	TAS-2B	--	0.0045	0.0006	0.0039	0.005	100	Slight oil in probe wash
4/8/77	TAS-2B	--	0.0164	0.0147	0.0017	0.002	100	Oil in probe wash
4/11/77	TAS-2A	0.0070	--	--	--	--	--	Boilerhouse air, no oil
4/12/77	TAS-2D	--	0.0259	0.0232	0.0027	0.003	100	Oil in probe wash
4/12/77	TAS-2D	--	0.0201	0.0164	0.0037	0.004	100	Oil in probe wash
4/12/77	TAS-2D	--	0.0044	0.0039	0.0005	0.001	100	Slight oil in probe wash
4/13/77	TAS-2A*	0.0014	0.0016	0.0004	0.0012	--	100	No oil
4/14/77	TAS-2A	0.0012	--	--	--	--	--	Ambient air, no oil
4/14/77	TAS-2A	0.0011	--	--	--	--	--	Ambient air, no oil
4/15/77	TAS-2F	--	0.0044	0.0019	0.0025	0.003	100	Trace of oil
4/18/77	TAS-2A	--	0.0029	0.0017	0.0012	0.001	100	Oil in probe wash
4/19/77	TAS-2A	--	0.0022	0.0008	0.0014	0.002	29	Oil in probe wash
4/20/77	TAS-2A	0.0013	--	--	--	--	--	No oil
6/1/77	TAS-2F	0.0098	0.0078	0.0002	0.0076	--	20	Boilerhouse air, no oil
5/2/77	TAS-2F	0.0015	0.0045	0.0002	0.0043	--	25	Ambient air, no oil
6/3/77	TAS-2A*	0.0006	0.0010	0.0000	0.0010	--	30	No oil

[1] Estimated oil free outlet loading. Calculated by determining the probe wash/filter wt. ratio for oil free runs using slurry (runs used are marked with an asterisk) and increasing the filter loading in the contaminated samples by this fraction (0.19). Due to the uncertainty in this value, the loadings were rounded off.

* See note above.

Table 18-4

VENTURI/SPRAY TOWER AIR/SLURRY TEST RESULTS

Date	Run No.	Mass Loading, gr/dscf		Reheater Oil Valve, % Open
		Inlet	Outlet	
5/5/77	VAS-1A	--	0.0028	100%
5/9/77	VAS-1A	--	0.0017	100%
5/9/77	VAS-1A	--	0.0022	100%
5/11/77	VAS-1B	0.0008	0.0023	35%
5/11/77	VAS-1B	0.0007	0.0011	30%
5/12/77	VAS-1B	--	0.0015	33%
5/12/77	VAS-1C	--	0.0015	33%
5/13/77	VAS-1C	--	0.0021	35%
5/13/77	VAS-1C	--	0.0027	35%
5/16/77	VAS-1E	--	0.0027	30%
5/16/77	VAS-1E	--	0.0019	25%
5/17/77	VAS-1E	0.0021	0.0029	40%
5/18/77	VAS-1F	0.0014	0.0015	40%
5/19/77	VAS-1F	0.0011	0.0009	35%
5/20/77	VAS-1G *	0.0026	0.0010	40%

* Maximum Venturi $\Delta P = 9''$ WG

Table 18-5

RUN CONDITIONS FOR THE AIR/SLURRY TESTS ON THE TCA SYSTEM

	TAS-2A	TAS-2B	TAS-2D	TAS-2F
Recirculated slurry, gpm	1200	1200	1200	0
Equivalent inlet flue gas rate, acfm	30,000	20,000	30,000	30,000
Superficial gas velocity, ft/sec				
• TCA	12.5	8.4	12.5	12.5
• mist eliminator	8.2	5.5	8.2	8.2
Percent solids recirculated	15	15	15	--
Mist eliminator	3-pass, open-vane chevron	3-pass, open-vane chevron	3-pass, open-vane chevron	3-pass, open-vane chevron
Mist eliminator wash scheme	None	None	None	None
Bed Configuration	3 beds, 5 inches spheres/bed. Normal bed positions.	3 beds, 5 inches spheres/bed. Normal bed positions.	2 beds, 5 inches spheres/bed. Removed top bed.	3 beds, 5 inches spheres/bed. Normal bed positions.
Run Philosophy	Measure slurry entrainment at high gas rate.	Measure slurry entrainment at low gas rate.	Measure effect of no. of beds on slurry entrainment.	Measure reheater contribution to the mass loading.

Table 18-6

RUN CONDITIONS FOR THE AIR/SLURRY TESTS ON THE VENTURI/SPRAY TOWER SYSTEM

	VAS-1A	VAS-1B	VAS-1C	VAS-1E	VAS-1F	VAS-1G
Recirculated slurry, gpm (V/ST)	600/1400	600/1400	0/1400	0/0	600/0	600/0
Equivalent inlet flue gas rate, acfm	35,000	20,000	35,000	35,000	35,000	35,000
Superficial gas velocity, ft/sec						
• Spray tower	9.4	5.4	9.4	9.4	9.4	9.4
• Mist eliminator	9.4	5.4	9.4	9.4	9.4	9.4
Percent solids recirculated	8.0	8.0	8.0	--	8.0	8.0
Venturi ΔP, in. H_2O	9	9	9	--	9	14
Mist eliminator	3-pass, open-vane chevron	3-pass, open-vane chevron	3-pass, open-vane chevron	3-pass, open-vane chevron	3-pass, open-vane chevron	3-pass, open-vane chevron
Mist eliminator wash scheme	None	None	None	None	None	None
Run Philosophy	Measure slurry entrainment at high gas rate.	Measure slurry entrainment at low gas rate.	Measure effect of venturi on slurry entrainment.	Measure reheater contribution to the mass loading.	Measure effect of spray tower on slurry entrainment.	Measure effect of venturi pressure drop on slurry entrainment.

adjusted to provide a scrubber superficial air velocity equal to the scrubber superficial flue gas velocity at the specified inlet flue gas rate if flue gas had been used. After leaving the scrubber, the air was reheated and the resulting particulate mass loading was measured.

18.3.2 Discussion of Test Results

As can be seen in Tables 18-3 and 18-4, the inlet air mass loadings were of the same order of magnitude as the outlet mass loadings. Therefore, the determination of how much of the outlet mass loading measurement represented unremoved dust from the inlet air and how much was slurry entrainment was not possible. However, the amount of slurry emissions was less than or equal to the amount of outlet emissions since the latter consists of slurry entrainment, plus any dust not removed from the inlet air.

For the TCA scrubber, there was an additional complication. During testing, what appeared to be unburned fuel oil from the oil-fired reheater was found in the probe washes of the outlet mass loading tests. No oil accumulations had been experienced in previous testing on either system, and the source of oil could not be determined before testing was terminated due to routine maintenance scheduled during the boiler outage.

In early June 1977, three tests were run to investigate if the TCA oil problem could be resolved, but the problem apparently cleared up by itself since no oil was found in the outlet mass loading probe washes.

An oil-free slurry entrainment mass loading upper limit was calculated for the TCA by noting that during tests, when no oil was found, the outlet mass loading probe wash averaged 19 percent of the filter mass loading (see note, Table 18-3). Adding this percentage to the filter loading resulted in an upper limit for slurry entrainment of 0.001 to 0.005 grain/dry scf. The corresponding venturi/spray tower upper limit for slurry entrainment was 0.001 to 0.003 grain/dry scf.

An upper limit on the outlet moisture loading was estimated by assuming that the mass emissions during these tests represented solids from a slurry (TCA slurry was 16 weight percent total solids, venturi/spray tower slurry was 9 weight percent total solids) containing both suspended and dissolved solids. An estimated upper limit on the outlet moisture loading of 0.03 grain/dry scf (0.003 grain/dry scf upper limit of slurry solids entrainment for the venturi/spray tower, divided by 9 percent slurry concentration) was obtained for both systems. This appears to be a rather low moisture emission value for a three-pass, open-vane, chevron type mist eliminator unless the moisture loading to the mist eliminator is also very low.

Section 19

LIMESTONE REACTIVITY STUDY

Tests of limestone reactivity were conducted in the Shawnee laboratory to study the effect of limestone source and grind on reactivity and utilization. Limestones from eleven different quarries were studied; each stone was ground to fine and coarse sizes. Two laboratory methods were used to test reactivity: the HCL method and the SO_2 method. Results from the HCl method are presented in Subsection 19.2 and results from the SO_2 method are presented in Subsection 19.3. Recommendations for improvements in the laboratory methods are discussed in Subsection 19.4.

19.1 LABORATORY TEST PROGRAM

Limestones from different quarries vary in chemical composition and physical properties such as hardness, average pore size and pore size distribution, and porosity (void fraction). Both chemical and physical factors can affect the reactivity. Due to lack of equipment needed to determine these physical characteristics, it was not the attempt of this program to correlate the limestone reactivity values with physical properties.

The eleven limestones studied and their chemical compositions (as determined by TVA, Muscle Shoals) are listed in Table 19-1.

Table 19-1
LIMESTONES USED IN REACTIVITY TESTS

Limestone Source	Location	Chemical Composition, wt percent				Grind, percent less than	
		Calcium (Ca)	Magnesium (Mg)	Carbonate (CO_3)	Acid Insolubles	-200 Mesh	-325 Mesh
Citadel Stone Company	Selma, Alabama	32.5	0.2	47.4	14.8	94	93
Commonwealth Edison	Joliet, Illinois	37.9	1.4	56.6	3.5	65	78
Cowan Stone Company	Cowan, Tennessee	36.0	1.5	55.9	4.0	80	91
Fredonia Quarries	Fredonia, Kentucky	35.8	2.5	60.5	2.2	75	90
Georgia Marble	Sylacauga, Alabama	38.8	0.5	59.2	2.0	71	78
Hoover Incorporated	Nashville, Tennessee	36.6	1.2	54.1	3.8	92	84
Longview Lime Company	Longview, Alabama	38.2	0.7	59.9	1.0	72	77
Luttrell Mining Company	Knoxville, Tennessee	38.8	0.2	58.4	1.4	77	82
Rigsby & Barnard Quarry	Cave In Rock, Illinois	38.4	0.2	57.8	0.4	69	90
The Stone Man	Chattanooga, Tennessee	36.4	1.0	57.2	4.1	72	78
Vulcan Material Company	Knoxville, Tennessee	38.1	1.1	60.2	0.5	97	95

Since the reaction of limestone is a heterogeneous reaction, one would expect the reactivity to vary with surface area, which can be changed by grinding. Therefore, each limestone was tested at two different grinds. The limestones as received (generally 1/4 to 1 inch in size) were ground and screened at the International Fertilizer Development Corporation (IFDC) in Muscle Shoals, Alabama. Two samples of each limestone were prepared: a coarse grind of about 75 percent less than 200 mesh and a fine grind of about 90 percent less than 325 mesh. The actual measured grind for each sample as determined by wet screen analysis is given in Table 19-1.

19.2 LIMESTONE REACTIVITY BY THE HCl METHOD

The first method used to test limestone reactivity involved the addition of limestone to a solution of HCl. For each test, 5 grams of dried limestone were added to a 300-ml solution of HCl at pH 3 and 25°C, and the rise of pH with time was recorded.

19.2.1 Data Analysis

The original HCl method used the slope of the pH versus time curve at pH 4 for comparison of limestones. Due to the steepness of the curve, the slope could not be determined accurately. In addition, a reactivity value at pH 4 is not representative of the reactivity at normal scrubber operating pH's of 5 to 6. Inaccuracies also result if the initial pH's vary.

Due to these problems, an integral method of analysis was developed. When limestone reacts with a strong acid below pH 7, the following reactions predominate:

$$CaCO_3(s) + 2H^+ \rightarrow Ca^{++} + H_2CO_3$$

$$H_2CO_3 \rightarrow H^+ + HCO_3^-$$

The sum of these reactions is:

$$CaCO_3(s) + H^+ \rightarrow Ca^{++} + HCO_3^-$$

Thus, the rate of limestone dissolution equals the rate of hydrogen ion depletion. If reactivity is defined as the change in $CaCO_3$ concentration with time, then integration and rearrangement give [remembering that $pH = -\log_{10}(H^+)$]:

$$\text{Reactivity} \cong \frac{-d(CaCO_3)}{dt} = \frac{-d(H^+)}{dt} = \frac{-d(10^{-pH})}{dt} \cong \frac{10^{(-pH_1)} - 10^{(-pH_2)}}{t_2 - t_1}$$

For an initial pH of about 3 at time zero and a final pH of 7 at time t_2,

$$\text{Reactivity} \cong \frac{10^{(-pH_1)}}{t_2}$$

or

$$\text{Reactivity} = \frac{\text{Initial Hydrogen Ion Concentration of the HCL Aliquot, mmole/l}}{\text{Time to reach pH 7, min}} \qquad (19\text{-}1)$$

The strong effect of initial pH indicated by Equation 19-1 was experimentally proven during initial testing. As a result, only those tests where the initial pH was between 2.95 and 3.10 were used for the final anaylsis. Initial testing also showed that better mixing gave higher reactivity values.

Fifty-four tests were run on the twenty-two limestone samples and analyzed with Equation 19-1. Replication was done on a random basis. Of the fifty-four tests, eight were rejected because they were run during the off-shift without supervision and values were consistently high.

19.2.2 Reactivity Comparison by Source

Since all the limestones were not of the same grind, relative comparisons could not be made. However, for each grind specification, two to five different limestones could be compared. These comparisons are given in Table 19-2.

From the limited comparison possible, the Vulcan Materials Company limestone was the most reactive in the fine grind class (nominal 90 percent less 325 mesh), whereas the Stone Man limestone was the most reactive in the coarse grind class (nominal 70 percent less 200 mesh). The finely ground Vulcan limestone was about twice as reactive as the Fredonia fine limestone routinely used at Shawnee.

The least reactive limestones in the fine and coarse classes were the Fredonia Valley and the Georgia Marble varieties, respectively.

19.2.3 Reactivity Comparison by Grind

As expected, the reactivity increased with the fineness of the grind. Results from fine and coarse grind are rearranged by source and presented in Table 19-3. Once again, since all the limestones were not of the same grind, relative comparisons could not be made to evaluate the relative benefits of grind-

Table 19-2

REACTIVITY COMPARISON BY SOURCE
(HCl Method)

Limestone	Grind Mesh -200	Grind Mesh -325	Test No's.	Average Reactivity, mmole/l-min	Rank
The Stone Man	--	78	2, 26	3.16	1
Commonwealth Edison	--	78	6, 30	2.76	2
Georgia Marble	--	78	14, 38	2.10	3
Longview Lime Co.	--	77	52	1.23	4
Hoover Incorporated	--	84	7, 21, 31, 45	3.27	1
Luttrell Mining Co.	--	82	10, 34	2.88	2
Vulcan Material Co.	--	95	16, 24, 40, 48	5.44	1
Rigsby & Barnard	--	90	22, 17, 36, 41	3.56	2
Cowan Stone Co.	--	91	4, 19, 28, 43	3.17	3
Citadel Stone Co.	--	93	54	3.06	4
Fredonia Valley Quarries	--	90	50	2.66	5
The Stone Man	72	--	13, 23, 37, 47	3.00	1
Rigsby & Barnard	69	--	11, 35	2.12	2
Commonwealth Edison	65	--	1, 18, 25, 42	1.60	3
Longview Lime Co.	72	--	51	0.94	4
Georgia Marble	71	--	5, 27, 29, 44	0.90	5
Fredonia Valley Quarries	75	--	49	2.24	1
Cowan Stone Co.	80	--	3, 27	2.06	2
Luttrell Mining Co.	77	--	9, 22, 33, 46	1.68	3
Vulcan Material Co.	97	--	15, 39	3.81	1
Citadel Stone Co.	94	--	53	2.85	2
Hoover Incorporated	92	--	8, 32	2.40	3

Table 19-3

REACTIVITY COMPARISON BY GRIND (HCl Method)

Limestone Source	Grind Mesh -200	Grind Mesh -325	Test No.'s	Average Reactivity mmoles/l-min	Percent Increase in Reactivity
Citadel Stone Co.	94	--	53	2.85	7
	--	93	54	3.06	
Commonwealth Edison	65	--	1, 18, 25, 42	1.60	42
	--	78	2, 26	2.76	
Cowan Stone Co.	80	--	3, 27	2.06	35
	--	91	4, 19, 28, 43	3.17	
Fredonia Valley Quarries	75	--	49	2.24	16
	--	90	50	2.66	
Georgia Marble	71	--	5, 20, 29, 44	0.90	57
	--	78	6, 30	2.10	
Hoover Incorporated	92	--	8, 32	2.40	27
	--	84	7, 21, 31, 45	3.27	
Longview Lime Co.	72	--	51	0.94	24
	--	77	52	1.23	
Luttrell Mining Co.	77	--	9, 22, 33, 46	1.68	42
	--	82	10, 34	2.88	
Rigsby & Barnard	69	--	11, 35	2.12	40
	--	90	12, 17, 36, 41	3.56	
The Stone Man	72	--	13, 23, 37, 47	3.00	5
	--	78	14, 38	3.16	
Vulcan Materials Co.	97	--	15, 39	3.81	30
	--	95	16, 24, 40, 48	5.44	

ing. Instead, the percentage increase in reactivity with grinding for each type of limestone was calculated. These percentage increases are shown in Table 19-3.

Grinding was the most effective in increasing reactivity for the Georgia Marble limestone and the least effective for the Stone Man variety. To explain this behavior, it is hypothesized that the low reactivity of the Georgia Marble limestone resulted from a combination of low porosity and small pore size. When this limestone was crushed to make smaller particles, new surface was exposed at the points of fracture, and thus a strong dependence on reactivity with particle size was observed. Unlike the Georgia Marble variety, it is believed that the Stone Man limestone had relatively large pores and therefore, exhibited a weak dependence on grinding. Because of lack of equipment, measurements of mean pore diameter and pore volume, usually determined using mercury intrusion tests, were not measured.

19.3 LIMESTONE REACTIVITY BY THE SO_2 TITRATION METHOD

The second method used to test limestone reactivity was an SO_2 titration of the limestone slurries. First, 0.2 mole of limestone was dissolved in two liters of distilled water (0.1 M $CaCO_3$) at 50°C until a constant pH was reached. Then, a constant stream (0.273 g-mole/hr) of pure SO_2 was added, and the pH drop with time was monitored.

This method, though somewhat more involved than the HCl method, was believed to be more representative in evaluating limestones to be used in SO_2 scrubbing systems because:

- The reaction products ($CaSO_3$, $CaSO_4$, etc.) are representative of the products formed during wet scrubbing of flue gas.
- Due to their insoluble nature, these reaction products may plug the limestone pores and thus reduce the reactivity of the limestone. Such effects would not be simulated in the HCl method where soluble reaction products were formed.
- The buffering effect, around a pH of 5.8, characteristic of limestone scrubbing systems, were more nearly approximated by this method.
- The acid produced by this method, sulfurous acid, was weak compared to HCl, a strong acid. For limestone scrubbing systems, sulfurous acid chemistry was dominant.
- The effects of subsaturation, supersaturation, and blinding were more nearly approximated.

19.3.1 Data Analysis

A total of thirty-three SO_2 titrations were run on the twenty-two limestone samples. Replication was done on a random basis to insure validity.

Data were collected as a pH versus time curve. Results were compared in terms of limestone utilization, as defined below:

$$\text{Percent Utilization at a Given pH} = \frac{\text{Time to Reach pH End-Point} \times SO_2 \text{ Feed Rate} \times 100}{\text{Amount of Limestone}}$$

$$= \frac{\text{Time to Reach pH} \times 0.273 \text{ g-moles } SO_2/\text{hr} \times 100}{0.2 \text{ g-moles of limestone}}$$

19.3.2 Utilization (Reactivity) Comparison by Source

Since all the limestones were not of the same grind, relative comparison could not be made. However, for each grind class, two to five limestones could be compared. These comparisons are given in Table 19-4.

Table 19-4

UTILIZATION COMPARISON BY SOURCE
(SO_2 Titration)

Limestone Source	Grind Mesh -200	Grind Mesh -325	Test No.'s	Average Utilization at pH 5.4, %	Rank
The Stone Man	--	78	14, 14R	61.9	1
Commonwealth Edison	--	78	2, 2R	61.4	2
Longview Lime Co.	--	77	20, 20R	59.2	3
Georgia Marble	--	78	6	40.9	4
Luttrell Mining Co.	--	82	10, 10R	63.2	1
Hoover Incorporated	--	84	7	38.7	2
Rigsby & Barnard	--	90	12, 12R	100.0	1
Fredonia Valley Quarries	--	90	22, 22R	95.5	2
Vulcan Material Co.	--	95	16, 16R	89.9	3
Citadel Stone Co.	--	93	18	64.8	4
Cowan Stone Co.	--	91	4	47.8	5
Rigsby & Barnard	69	--	11, 11R	72.8	1
The Stone Man	72	--	13	40.9	2
Commonwealth Edison	65	--	1	39.8	3
Georgia Marble	71	--	5, 5R	30.7	4
Longview Lime Co.	72	--	19	23.9	5
Fredonia Valley Quarries	75	--	21, 21R	50.5	1
Luttrell Mining Co.	77	--	9	40.9	2
Cowan Stone Co.	80	--	3, 3R	37.1	3
Citadel Stone Co.	94	--	17	69.4	1
Vulcan Materials Co.	97	--	15	60.3	2
Hoover Incorporated	92	--	8	38.7	3

From the limited comparison possible, the Rigsby & Barnard limestone was found to be the most reactive in both the fine grind (nominal 90 percent less than 325 mesh) and the coarse grind (nominal 70 percent less than 200 mesh) classes. Fredonia fine limestone used at Shawnee ranked second best in the fine grind class.

19.3.3 Utilization Comparison by Grind

As in the HCl method results, finer limestones had higher reactivities than their coarser counterparts, as shown in Table 19-5.

As before, the benefits of grinding could not be evaluated for all the samples. If the variability of the size cuts is ignored, one finds that finer grinding is most beneficial for the Longview and the Fredonia limestones and least beneficial for the Hoover Incorporated and Citadel Stone varieties. The percentage increases in utilization with finer grinding are given in Table 19-5.

19.4 COMPARISON OF AND RECOMMENDATIONS FOR THE HCl AND SO_2 TITRATION METHODS

In general, the SO_2 method was judged to be superior to the HCl method because it more closely approximated SO_2 scrubbing with limestone (see Subsection 19.3). Due to the disparity of the methods, the data were not comparable. Shortcomings of the SO_2 method include the complexity of the equipment and the time per test (one hour for the SO_2 method and five minutes for the HCl method).

Table 19-5

UTILIZATION COMPARISON BY GRIND
(SO_2 Titration)

Limestone Source	Grind Mesh -200	Grind Mesh -325	Test No.'s	Average Utilization at pH 5.4, %	Increase in Utilization at pH 5.4
Citadel Stone Co.	94	--	17	69.4	-7
	--	93	18	64.8	
Commonwealth Edison	65	--	1	39.8	35
	--	78	2, 2R	61.4	
Cowan Stone Co.	80	--	3, 3R	37.1	22
	--	91	4	47.8	
Fredonia Valley Quarries	75	--	21, 21R	50.5	47
	--	90	22, 22R	95.5	
Georgia Marble	71	--	5, 5R	30.7	25
	--	78	6	40.9	
Hoover Incorporated	92	--	8	38.7	0
	--	84	7	38.7	
Longview Lime Co.	72	--	19	23.9	60
	--	77	20, 20R	59.1	
Luttrell Mining Co.	77	--	9	40.9	35
	--	82	10, 10R	63.2	
Rigsby & Barnard	69	--	11, 11R	72.8	27
	--	90	12, 12R	100.0	
The Stone Man	72	--	13	40.9	34
	--	78	14, 14R	61.9	
Vulcan Materials Co.	97	--	15	60.3	33
	--	95	16, 16R	89.9	

The HCl method could be improved by increasing the amount of HCl solution at pH 3 from 300 ml to one liter and decreasing the limestone sample from 5 grams to 0.1 gram, thus diluting the slurry and making it less subject to pH fluctuations. In addition, the slope method should be discarded in favor of the integral method described in Subsection 19.2.

The SO_2 titration method assumes that there is a complete reaction between the SO_2 and the limestone. Use of an SO_2 analyzer on the offgas would improve this method. Utilization could then be calculated from the amount of SO_2 absorbed rather than from the amount of SO_2 entering the system.

Both methods would be more reproducible if the limestone samples were more uniform. During SO_2 titration tests, the initial pH of the limestone slurry in water varied as much as 1.3 pH units for limestone samples taken from the same container. This could be caused by nonuniform chemical or physical properties, nonuniform grinding, and/or settling during transportation.

Better correlations with limestone type could be made if values of physical properties such as hardness, density, porosity, and average pore size were available.

19.5 PILOT PLANT TEST PROGRAM

To verify the ranking by reactivity or utilization of a few of the limestones and to gain a better insight into the role of physical properties of the limestone, a test program to conduct limestone type and grind tests on a pilot scrubber has been developed. Salient features of this program are described below.

19.5.1 Limestone Preparation

The limestone samples will be procured by TVA and ground at the Allis-Chalmers grinding test facility in Milwaukee, Wisconsin. Allis-Chalmers will also prepare the samples for the Martin Marietta test laboratory in Baltimore, Maryland. At this laboratory, chemical composition, petrographic features, specific surface area, and reactivity will be determined.

19.5.2 Limestone Type

The four limestones to be tested include Fredonia, Stone Man (Tiftonia), Georgia Marble, and Rigsby and Barnard. Two more limestones may be added later.

19.5.3 Test Program

Testing will be done on the pilot scrubber operated by the EPA at Research Triangle Park (RTP), North Carolina. The RTP pilot plant will be run under the following conditions:

- TCA scrubber with internals to provide 8 inches H_2O of pressure drop
- 8 percent solids in recirculating slurry
- No fly ash
- 12.5 ft/sec (3.8 m/sec) superficial gas velocity
- 50 gal/Mcf liquid-to-gas ratio
- 3000 ppm SO_2 inlet
- 5000 ppm Cl in liquor
- 9 minutes' residence time (single hold tank)

Stoichiometry will vary with limestone type and grind. Selection of stoichiometry is discussed below.

The pilot plant test runs are expected to last ten days each. At a feed stoichiometry of 1.2 and an SO_2 removal of 80 percent, the limestone feed rate is 11.8 lb/hr or 1400 lb/5-day period.

The following tests have been planned for the RTP scrubber*:

Weeks 1 and 2	Coarse Fredonia (high stoichiometry)
3 and 4	Coarse Fredonia (medium stoichiometry)
5 and 6	Coarse Fredonia (low stoichiometry)
7 and 8	Very Coarse Fredonia
9 and 10	Fine Fredonia
11 and 12	Coarse Stone Man
13 and 14	Fine Stone Man
15 and 16	Coarse Georgia Marble
17 and 18	Fine Georgia Marble
19 and 20	Coarse Rigsby and Barnard
21 and 22	Fine Rigsby and Barnard

where nominally fine = 90% less than 325 mesh
coarse = 75% less than 200 mesh
very coarse = 60% less than 200 mesh

19.5.4 Limestone Type and Grind Control Method

A different control method will be utilized for the pilot plant tests. Ideally the limestones should be compared at the same SO_2 removal. However, the pilot plant is designed for stoichiometric control. An estimate of SO_2 removal versus stoichiometry will be made for each limestone by the following method. Coarse (75 percent less than 200 mesh) Fredonia limestone will be tested at three different stoichiometries to give a curve of stoichiometry versus SO_2 removal. On the basis of this curve, an SO_2 removal control point will be chosen. It will be assumed that SO_2 removal depends primarily on total limestone surface area. The total surface area is the product of the specific surface area (m^2/g, measured by Martin Marietta) and the limestone feed rate (g/time). The limestone feed rate for each type and grind test will be set so that total surface area is constant and is equal to the total surface area of Fredonia coarse at the SO_2 removal control point. This should give a constant SO_2 removal at varying stoichiometries. In practice, the SO_2 removal from each test will differ from the selected SO_2 removal control point. It will then be assumed that the SO_2 removal versus stoichiometry curve for each type and grind will be parallel to the curve for Fredonia coarse. Comparisons will be made on the basis of varying stoichiometry at the SO_2 removal control point.

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*Two other limestones will be tested later.

After testing at the RTP pilot plant, the results for selected limestone types and grinds will be confirmed by tests at the Shawnee Test Facility.

Section 20

FLUE GAS PRESSURE DROP CORRELATIONS

20.1 SPRAY TOWER PRESSURE DROP CORRELATION

The flue gas pressure drop across the four slurry headers in the spray tower was measured as a function of superficial gas velocity, total slurry flow rate, and number and position of the headers in use. These measurements were taken during venturi/spray tower Run 820-1A (see Section 6) before steady state was reached for the run.

Figure 20-1 shows the flue gas pressure drop as a function of superficial gas velocity and slurry flow rate with all four spray headers in use. Figure 20-2 presents the effect of the number and position of spray headers on the flue gas pressure drop at 14 gpm/ft^2 total slurry flow rate.

The top three headers sprayed slurry downward and the bottom header sprayed slurry upward (see Figure 3-1). Each header had seven Bete No. ST48FCN nozzles. The vertical distance between the spray headers was approximately 4 feet. The pressure drops across the four headers were measured by pressure differential indicator PDI-1012. The lower pressure tap was located 20 inches below the centerline of the bottom header and the upper tap 7 inches above the centerline of the top header.

Equation 20-1 gives flue gas pressure drop as a function of gas and slurry

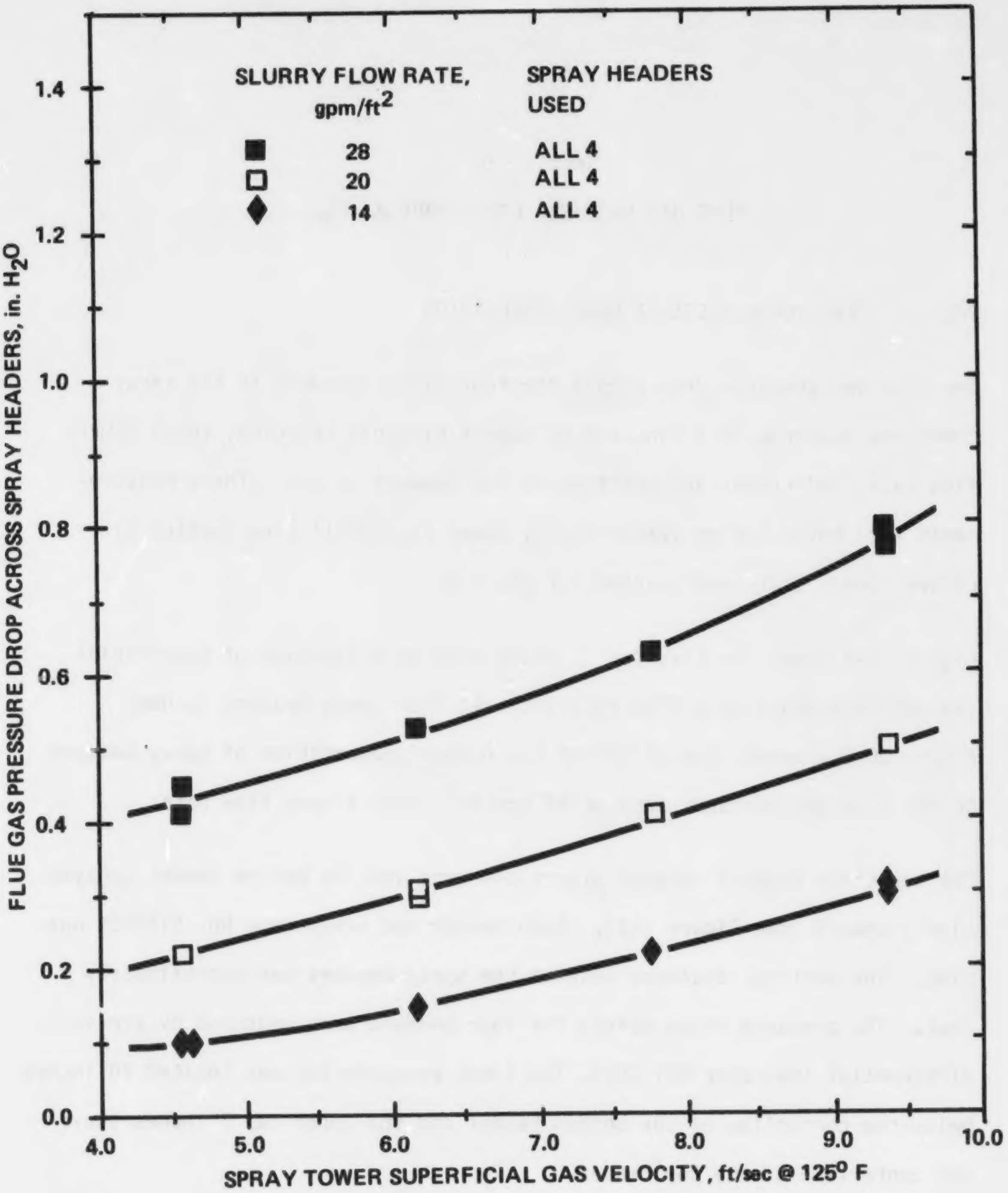

Figure 20-1

The Effect of Gas Velocity and Slurry Flow Rate on the Flue Gas Pressure Drop Across the Four Slurry Headers (7 Nozzles/Header) in the Spray Tower

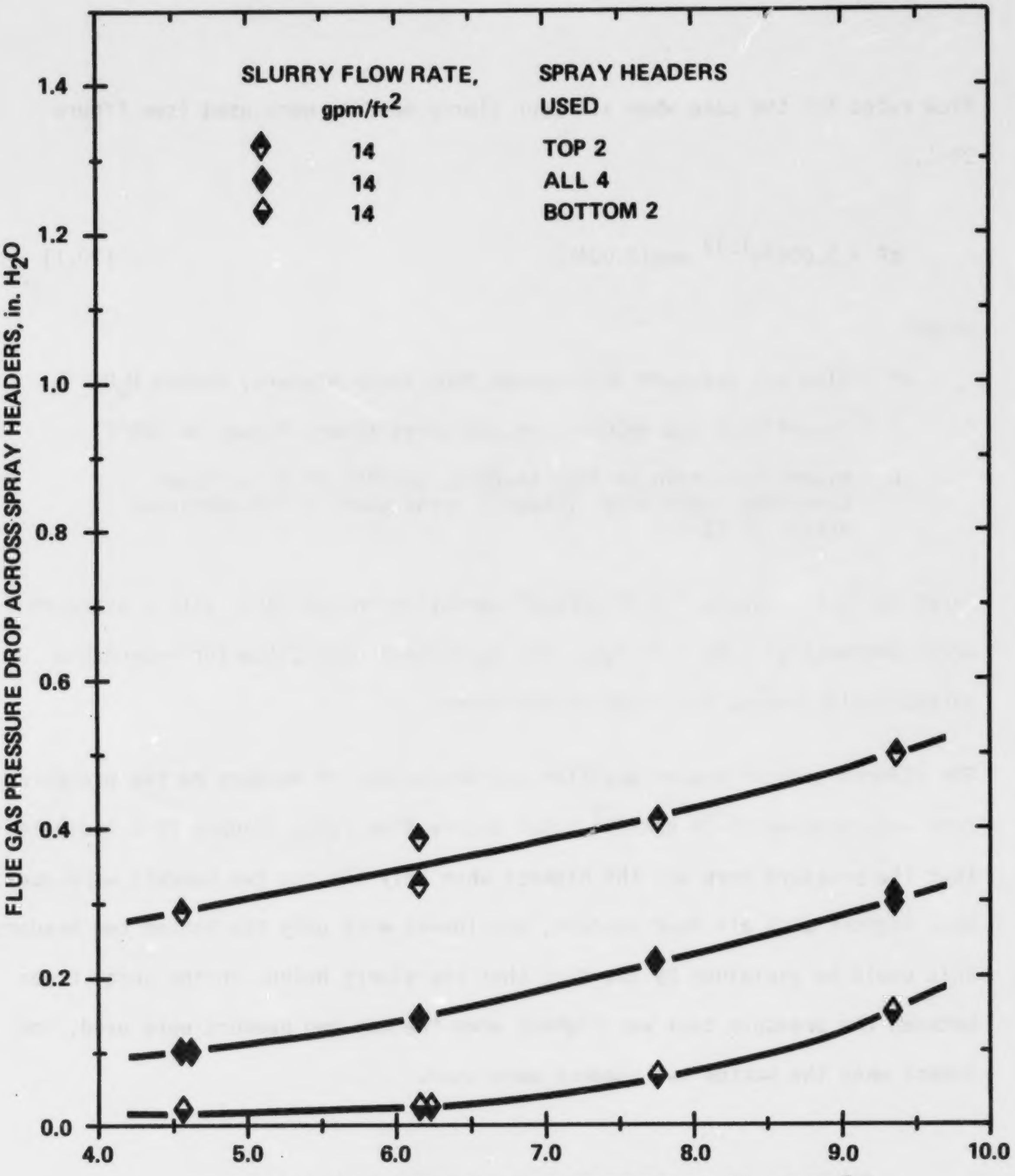

Figure 20-2

The Effect of Header Position and Number of Headers (7 Nozzles/Header) on the Flue Gas Pressure Drop at 14 gpm/ft^2 Total Slurry Flow Rate flow rates for the case when all four slurry headers were used (see Figure 20-1):

$$\Delta P = 0.0063v^{1.17} \exp(0.084L) \quad (20\text{-}1)$$

where:

ΔP = flue gas pressure drop across four spray headers, inches H_2O

v = superficial gas velocity in the spray tower, ft/sec at 125°F

L = slurry flow rate to four headers, gpm/ft^2 of spray tower cross-sectional area (Shawnee spray tower cross-sectional area = 50 ft^2)

Equation 20-1 accounts for 92 percent variation in the data, with a standard error estimate of 0.06 inch H_2O. The equation should allow for reasonable extrapolation beyond the range of operation.

The effects of both header position and the number of headers on the pressure drop were studied at 14 gpm/ft^2 total slurry flow rate. Figure 20-2 indicates that the pressure drop was the highest when only the top two headers were used, next highest with all four headers, and lowest with only the bottom two headers. This could be explained by the fact that the slurry holdup in the spray tower between the pressure taps was highest when the top two headers were used, and lowest when the bottom two headers were used.

20.2 TCA PRESSURE DROP CORRELATION AND HOLDUP TESTING

A series of air/water pressure drop and liquid holdup tests were made on the TCA during the April-June 1977 boiler outage. Pressure drop data were used to determine flooding conditions. Flooding is characterized by a large increase in pressure drop for a small increase in gas velocity, and by large fluctuations in pressure drop at constant gas velocity. The data indicated that flooding usually occurred at 8 to 10 inches H_2O for the three-bed TCA independent of ball depth. Liquid holdup in the scrubber ranged from 40 to 250 gallons.

The pressure drop and liquid holdup tests were made with 0, 5, 7.5, and 10 inches per bed (3 beds, 4 grids) of 6.5-gram, 1-5/8 inch nitrile foam spheres. Water flow rates ranged from 19 to 44 gal/min-ft^2. Superficial air velocities varied from 7.5 to 13 ft/sec in the pressure drop tests, and from 1 to 11.4 ft/sec. in the liquid holdup tests. The cross-sectional area of the Shawnee TCA is 32 ft^2.

20.2.1 TCA Pressure Drop Test Results

The results of the pressure drop tests are presented in Figures 20-3 through 20-6. The figures show that pressure drop across the TCA beds increased with increasing liquor flow rate and increasing air velocity.

Measured pressure drops for runs made at the same conditions (replicate runs) were in good agreement. Measured pressure drops were the same regardless of whether the test conditions were reached by increasing or decreasing the air velocities.

A comparison of Figures 20-3 through 20-5 with earlier TCA pressure drop tests (Reference 2) using high-density polyethylene (HDPE) and thermoplastic rubber (TPR) spheres shows good agreement (within 1/2 inch H_2O) at pressure drops below 9 inches H_2O. However, the 5-gram HDPE spheres and the 5-gram TPR

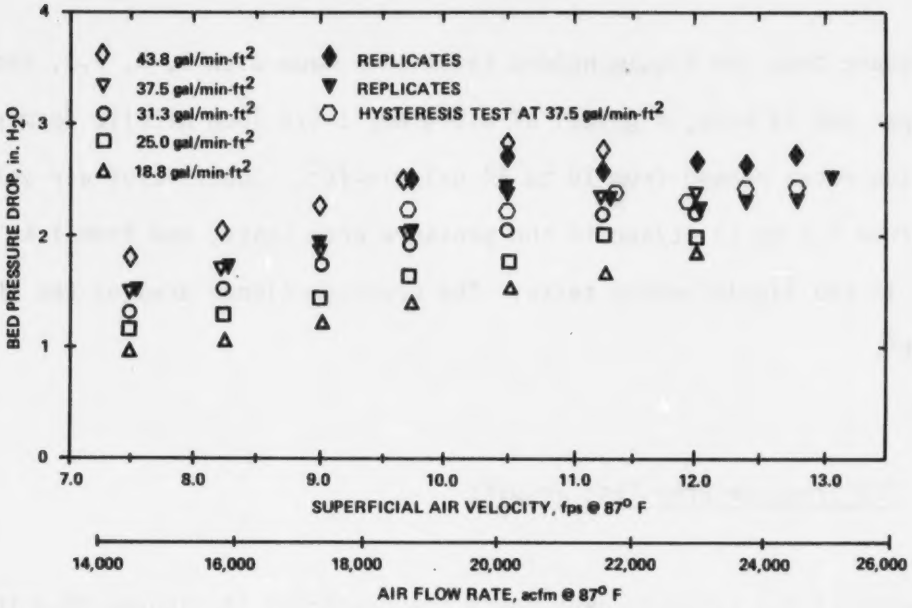

Figure 20-3. TCA Bed Pressure Drop (3 Beds, 4 Grids) - 0 inches Total Bed Height of Nitrile Foam Spheres

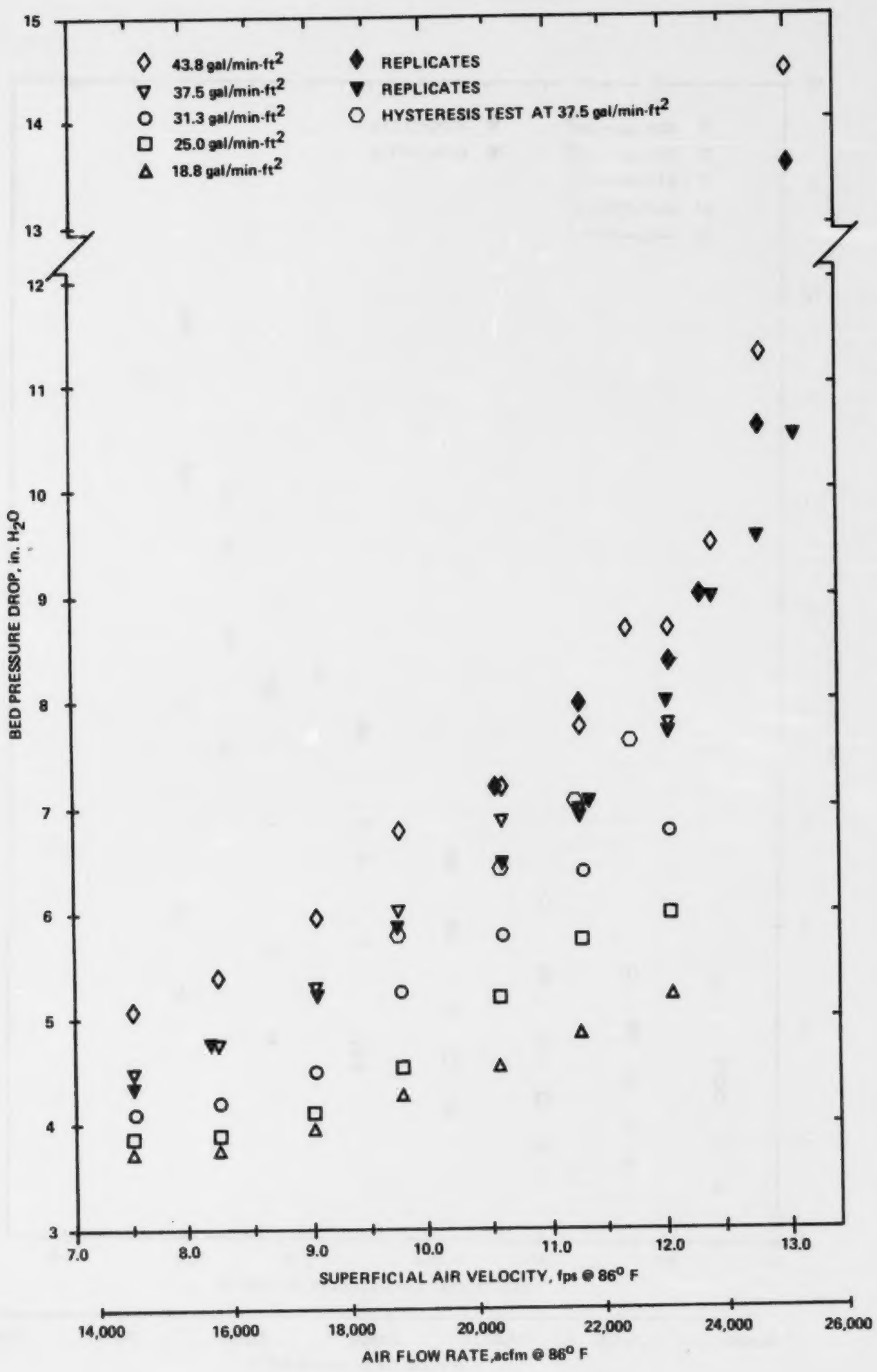

Figure 20-4. TCA Bed Pressure Drop (3 Beds, 4 Grids) -
15 inches Total Bed Height of Nitrile Foam Spheres

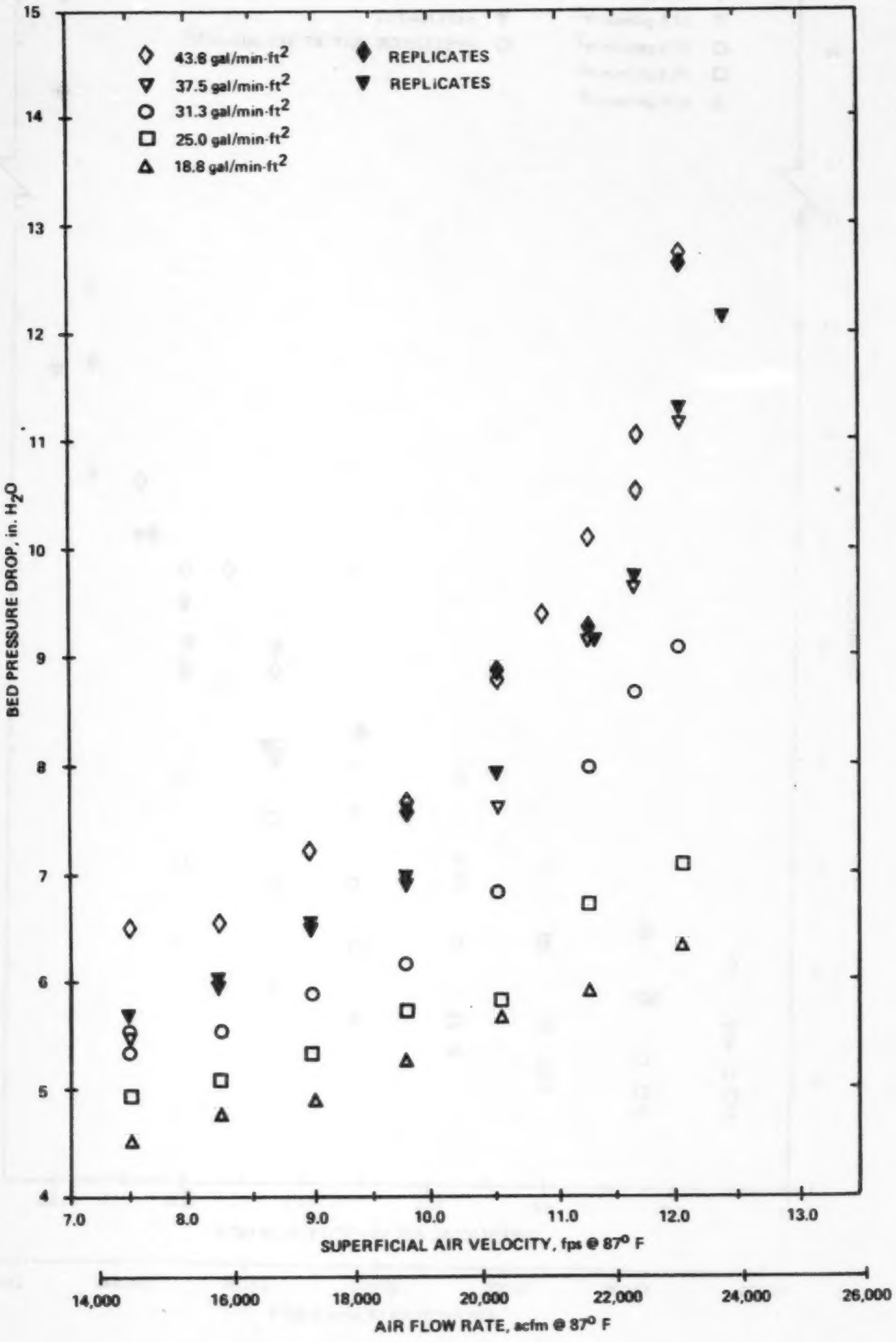

Figure 20-5. TCA Bed Pressure Drop (3 Beds, 4 Grids) - 22.5 inches Total Bed Height of Nitrile Foam Spheres

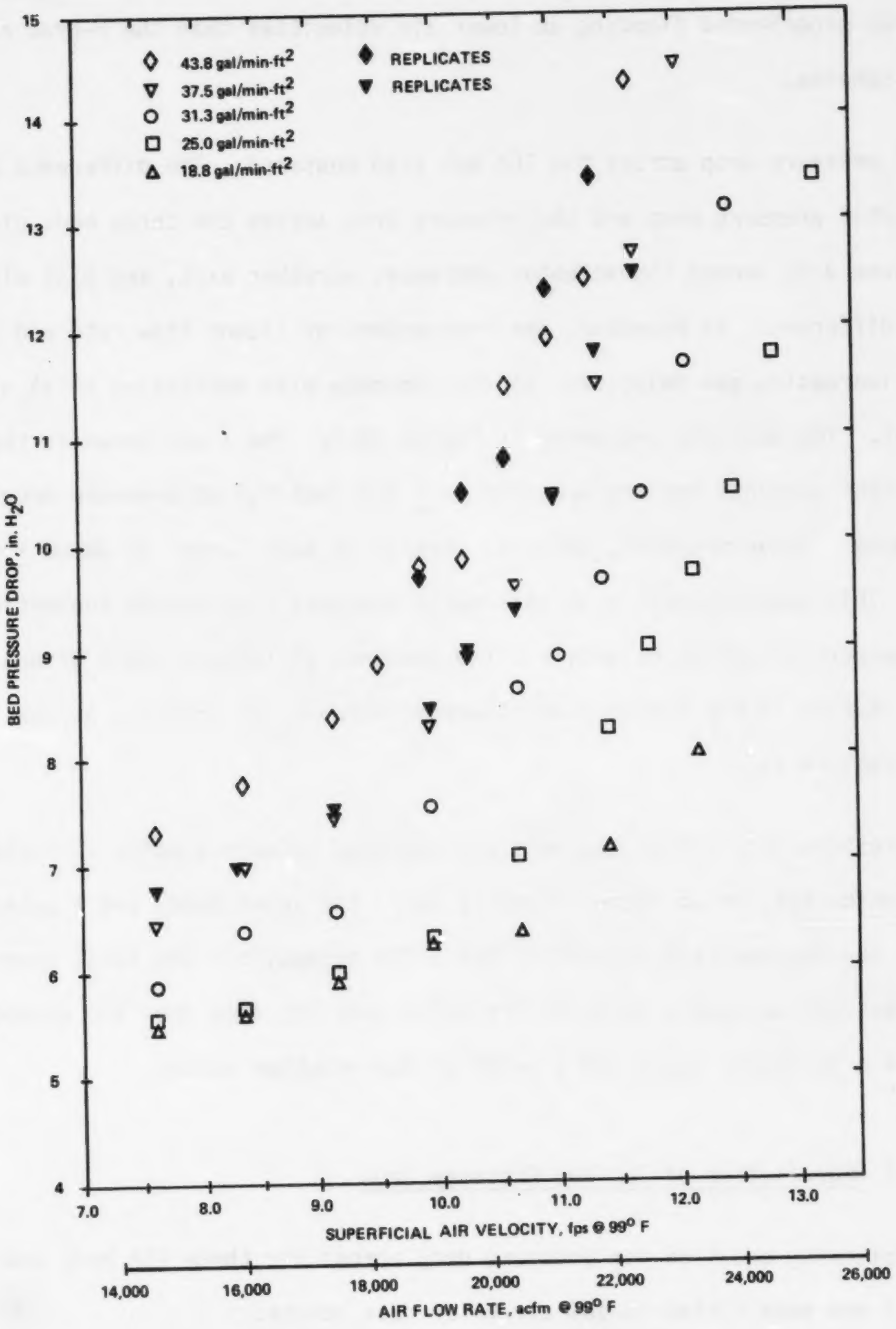

Figure 20-6. TCA Bed Pressure Drop (3 Beds, 4 Grids) - 30 inches Total Bed Height of Nitrile Foam Spheres

spheres experienced flooding at lower air velocities than the 6-gram nitrile foam spheres.

Total pressure drop across the TCA was also measured. The difference between the total pressure drop and the pressure drop across the three beds gives the pressure drop across the scrubber entrance, scrubber exit, and mist eliminator. This difference, as expected, was independent of liquor flow rate and increased with increasing gas velocity; it did increase with decreasing total sphere height. The data are presented in Figure 20-7. The lines shown in the figure are sight averages and are accurate to ± 0.1 inch H_2O at pressure drops below flooding. Above flooding, the data scatter is much larger at about ± 0.5 inches H_2O. This entrance/exit mist eliminator pressure drop should theoretically be independent of sphere height, but the presence of spheres might affect the gas distribution in the scrubber and thereby increase the pressure at the lower bed pressure tap.

The pressure drop across the beds was measured between a point 28 inches below the bottom bed, or 35 inches directly above the inlet duct, and a point 40 inches above the top bed (see Figure 3-2 for a TCA schematic). The total pressure drop was measured between a point in the inlet duct (22 feet from the scrubber inlet, before a 90 degree turn) and a point at the scrubber outlet.

20.2.2 Correlation of TCA Bed Pressure Drop

The following equation for pressure drop across the three TCA beds and four grids* has been fitted to 164 air/water data points:

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* The grids consist of 3/8-inch diameter bars with a center-to-center distance of 1-1/4 inches.

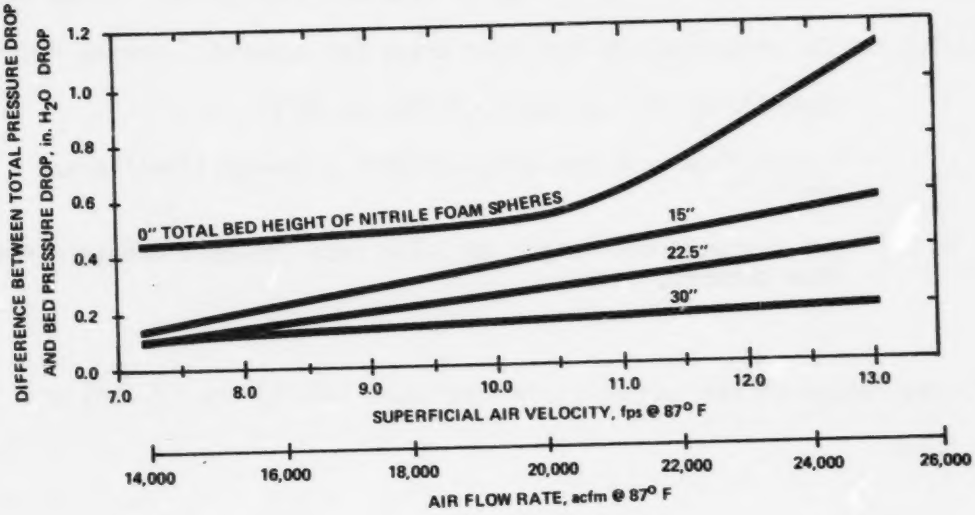

Figure 20-7. Difference Between TCA Total Pressure Drop and Bed Pressure Drop

$$\Delta P = (\Delta P)_{NS} + 0.0363\, v\, H_S^{0.69} \exp(0.014\, L) \quad (20\text{-}2a)$$

with

$$(\Delta P)_{NS} = 0.095\, v \exp(0.021\, L) \quad (20\text{-}2b)$$

where:

ΔP = TCA pressure drop for three beds and four grids, inches H_2O**

$(\Delta P)_{NS}$ = TCA pressure drop for four grids (no spheres), inches H_2O**

v = superficial air velocity, ft/sec at 90°F

L = liquor flow rate per unit scrubber cross-sectional area, gpm/ft^2*

H_S = total static bed height of 1-5/8 inch diameter 6.5-gram nitrile foam spheres, inch

The fitted ranges of the variables in Equations (20-2a) and (20-2b) are given below:

ΔP = 0.9 to 8.0 inches H_2O

v = 7.6 to 13.1 ft/sec

L = 19 to 44 gpm/ft^2

H_S = 0 to 30 inches

All measured pressure drops in excess of 8.0 inches H_2O were excluded from the correlation because of incipient flooding. Any case for which Equation (20-2a) predicts a pressure drop greater than 8.0 inches H_2O is likely to be in the flooding region.

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* TCA cross-sectional area in 32 ft^2.

** Measured from below the bottom grid to above the top grid.

Measured TCA bed pressure drops with spheres (107 data points) and the corresponding predictions from Equation (20-2a) are shown in Figure 20-8. Equation (20-2a) accounts for 96 percent of the variation in the data with a standard error of estimate of 0.24 inch H_2O.

Measured TCA bed pressure drops without spheres (57 data points) and the corresponding predictions from Equation (20-2b) are shown in Figure 20-9. Equation (20-2b) accounts for 90 percent of the variation with a standard error of 0.15 inch H_2O.

For the overall (spheres and no spheres) data, Equation (20-2a) explains 99 percent of the variation, with a standard error of 0.21 inch H_2O.

The form of Equation (20-2a) was chosen to meet boundary constraints on pressure drop for limiting values v, L, and H_S. For example, the equation predicts zero pressure drop at zero gas velocity.

20.2.3 TCA Liquid Holdup Test Results

Liquid holdup was measured as the difference in effluent hold tank level between down conditions (slurry pump off) and test conditions. The measured test data are given in Table 20-1. As measured, the liquid holdup included piping and downcomer holdup as well as holdup in the scrubber. To estimate piping and downcomer holdup, tests were made with zero air velocity and no spheres. Holdup was approximately 264 gallons at these minimum conditions. However, even with zero velocity and no spheres, there is some holdup in

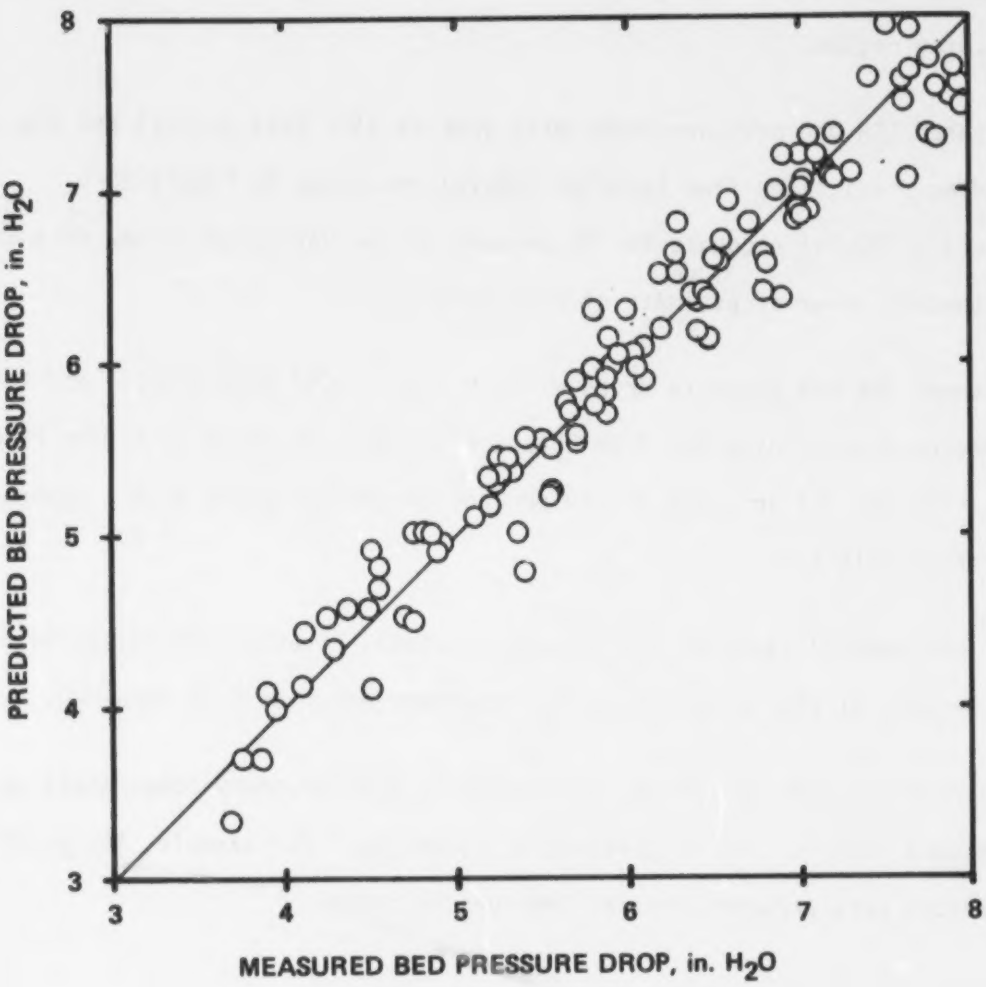


Figure 20-8. Comparison of Experimental Data and Predicted Values of Bed Pressure Drop - Three-Stage TCA with 1-5/8 inch Dia., 6.5 gram Solid Nitrile Foam Spheres

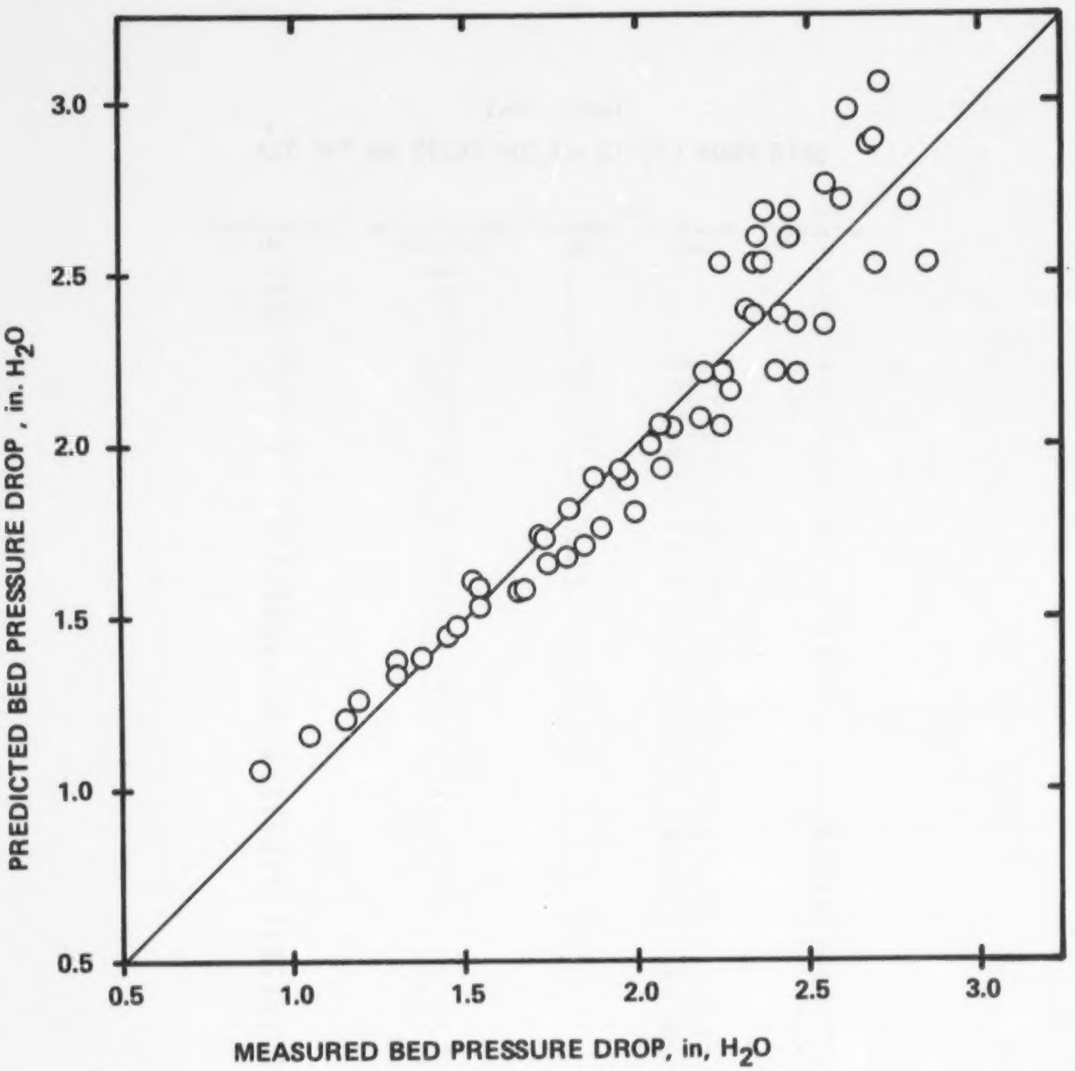


Figure 20-9. Comparison of Experimental Data and Predicted Values of Bed Pressure Drop - Three-Stage TCA without Spheres

Table 20-1

DATA FROM LIQUID HOLDUP TESTS ON THE TCA

Total Bed Height, in	Air Flow Rate, acfm	Air Velocity, fps	Liquor Flow Rate, gal/min-ft^2	Liquid Holdup,* gal
0	0	0	18.8	264
0	0	0	28.1	264
0	0	0	37.5	264
0	0	0	43.8	312
0	0	0	43.8	312
0	14,400	7.5	18.8	240
0	17,900	9.3	18.8	264
0	21,600	11.2	18.8	282
0	14,400	7.5	28.1	276
0	17,900	9.3	28.1	264
0	21,600	11.2	28.1	294
0	14,400	7.5	37.5	288
0	17,900	9.3	37.5	312
0	21,600	11.2	37.5	288
0	14,400	7.5	37.5	288
0	21,600	11.2	37.5	252
0	14,400	7.5	43.8	288
0	17,900	9.3	43.8	300
0	21,600	11.2	43.8	288
15	14,300	7.5	18.8	282
15	17,850	9.3	18.8	300
15	21,500	11.2	18.8	324
15	14,300	7.5	28.1	288
15	17,850	9.3	28.1	336
15	21,500	11.2	28.1	336
15	14,300	7.5	37.5	363
15	17,900	9.3	37.5	420
15	21,500	11.2	37.5	408
15	14,300	7.5	43.8	390
15	17,850	9.4	44.4	384
15	21,500	11.2	43.8	408
22.5	14,300	7.5	18.8	288
22.5	17,900	9.3	18.8	264
22.5	21,500	11.2	18.8	324
22.5	14,300	7.5	28.1	324
22.5	17,900	9.3	28.1	312
22.5	21,500	11.2	28.1	372
22.5	14,300	7.5	37.5	324
22.5	17,900	9.3	37.5	348
22.5	21,500	11.2	37.5	408
22.5	14,300	7.5	37.5	348
22.5	21,500	11.2	37.5	384
22.5	14,300	7.5	43.8	288
22.5	17,900	9.3	43.8	384
22.5	21,500	11.2	43.8	408
22.5	14,300	7.5	43.8	360
22.5	21,500	11.2	43.8	408
30	14,700	7.6	18.8	312
30	18,000	9.5	18.8	312
30	22,000	11.4	18.8	336
30	14,700	7.6	28.1	348
30	18,000	9.5	28.1	360
30	22,000	11.4	28.1	396
30	14,700	7.6	37.5	360
30	18,000	9.5	37.5	420
30	22,000	11.4	37.5	408
30	14,700	7.6	37.5	396
30	22,000	11.4	37.5	468
30	14,700	7.6	43.8	384
30	18,000	9.5	43.8	420
30	22,000	11.4	43.8	492
30	18,000	9.5	43.8	432
30	14,700	7.6	43.8	408

* Difference in tank level between having the pump on and the pump off. Includes holdup in the piping and downcomer.

the scrubber as the liquid travels the length of the scrubber. Assuming the liquid falls directly from the inlet spray header to the outlet, the minimum scrubber holdup was estimated as 64 gallons by taking the cross-sectional area of the feed pipe (7.9-inch ID) multiplied by the distance between the inlet header and the outlet (24.7 feet). Therefore, the piping and downcomer holdup was estimated as 200 gallons (264 gallons holdup with zero air rate and no spheres, minus 64 gallons estimated scrubber holdup at this minimum condition). This estimated piping and downcomer holdup was subtracted from the measured liquid holdup in all tests to estimate the net scrubber holdup.

Scrubber holdup ranged from 40 to 250 gallons over the range of conditions studied. Volumes were accurate to ± 25 gallons. Scrubber holdup under typical operating conditions and the effect on holdup of changing major conditions are summarized below:

Typical operating conditions of 11.2 ft/sec, 37.5 gal/min-ft$_2$, and 15 inches total sphere height	210-gallon scrubber holdup
Effect of air velocity increase from 7.5 to 11.2 ft/sec	Holdup increase by 20 to 60 gallons
Effect of liquor rate increase from 18.8 to 37.5 gal/min-ft$_2$	Holdup increase by 40 to 120 gallons
Effect of sphere height increase from 0 to 30 inches	Holdup increase by 70 to 110 gallons

Section 21

ANALYSIS OF SLURRY LIQUOR FOR SELECTED TRACE METALS, NITROGEN, AND ORGANIC CARBON

21.1 ANALYSIS PROGRAM

On July 2, 1977, during forced-oxidation Run 856-1A on the venturi/spray tower system, the sulfite oxidation decreased from 95 percent to a low of 62 percent for no apparent reason. The oxidation then gradually increased to 95 percent by July 5. During the same period, a similar decrease occurred in the TCA system, Run 802-2A, from 45 to 14 percent oxidation. No similar unexplained decrease in oxidation efficiency was observed throughout the forced-oxidation test program.

Since both systems reacted nearly simultaneously, it is postulated that a contaminant was introduced with the flue gas or makeup water. This contaminant either inhibited oxidation directly, perhaps by acting as a radical scavenger, or inhibited oxidation indirectly by reducing the catalytic activity of certain trace metals.

As a result of this phenomenon, a program of routinely analyzing trace metals, nitrogen, and organic carbon was initiated. It is hoped that if the conditions that inhibited oxidation recur, these tests will help identify the source.

Not only can the analysis of trace metals help identify an oxidation anomaly, but it can also document the effects that the scrubber environment has on the materials from which the scrubber system is constructed.

TVA's Power Service Center Laboratory in Chattanooga, Tennessee, performed the nitrogen and carbon analyses. TVA's General Analytical Laboratory in Muscle Shoals, Alabama, performed the trace metal analyses.

21.2 TRACE METALS

Table 21-1 presents the results of the analysis of the venturi inlet and the TCA outlet (see Figure 2-1) slurry liquor samples for selected trace metals as reported by TVA. These sample locations were picked so the effects of natural oxidation could most easily be discerned.

Metals with the highest catalytic characteristics for sulfite oxidation were selected. Because the venturi/spray tower operated with a tighter water balance than did the TCA system, concentrations were generally higher in the venturi/spray tower system.

21.2.1 Cobalt (Co), Chromium (Cr), Copper (Cu)

The concentrations of cobalt, chromium, and copper were relatively low and invariant. In January 1978, these components were dropped and replaced with titanium and vanadium.

Table 21-1
RESULTS OF SLURRY LIQUOR ANALYSIS

SYSTEM	TYPE OF RUN			TRACE METALS									No_x	TOC	pH	ADDITIVE
	Alkali	Oxidation(1)	Fly Ash Loading	Co	Cr	Cu	Fe	Mn	Mo	Ni	Ti	V				
V/ST	L	Yes	Low	0.2	0.06	0.03	0.02	10	1	0.5	-	-	-	-	8.0	-
V/ST	LS	Yes	Low	0.2	0.02	0.02	0.2	28	1	0.8	-	-	22	9	6.0	-
V/ST	LS	Yes	High	0.7	0.02	0.08	0.2	62	8	1.4	-	-	50	3	5.9	-
V/ST	L	Yes	High	0.4	0.01	0.08	0.5	36	5	1.2	0.5	0.5	59	5	7.8	-
V/ST	LS	Yes	High	-	-	-	23	55	6	1.2	0.4	1.3	42	3	6.0	MgO
V/ST	LS	Yes(2)	High	-	-	-	2.1	53	9	1.2	0.2	0.9	27	6	5.3	MgO
All V/ST	-	Yes	-	0.4	0.02	0.05	4.7	42	5	1.1	0.4	0.9	45	5	6.6	-
TCA	LS	Yes(3)	High	0.2	0.03	0.04	5	16	4	0.5	-	-	12	1.5	4.6	-
TCA	LS	No	High	0.1	Tr(4)	Tr	0.3	3	6	0.3	-	-	2	2	5.3	-
TCA	LS	Yes(5)	High	0.1	0.01	0.02	1.6	7	4	0.3	0.1	0.4	14	2	5.3	-
TCA	LS	No	High	-	-	-	6	3	6	0.3	0.4	1.5	21	3	5.5	MgO
TCA	LS	No	High	-	-	-	26	10	7	0.8	0.3	2	26	4	5.2	MgO
All TCA	-	-	-	0.1	0.02	0.02	7	7	5	0.4	0.3	1.5	15	2	5.2	-

Notes:

(1) Two-stage forced oxidation
(2) Bleed stream oxidation
(3) Air eductor used for oxidation
(4) Tr = Trace
(5) Air sparger used for oxidation

21.2.2 Iron (Fe)

The iron concentrations averaged 7 ppm in the TCA liquor and 5 ppm in the venturi liquor. Iron solubility increases with decreasing pH. This explains why iron concentrations were higher in the TCA, where the pH averaged 5.2, than in the venturi, where the pH averaged 5.5.

Iron concentrations in both systems were higher in runs made using MgO additive. Two effects influenced this. MgO runs were made at lower pH than most other runs during the period covered in this study (see Table 21-1); the presence of Mg^{++} enhances iron solubility via the common-ion effect.

21.2.3 Manganese (Mn)

The concentration of manganese in the venturi averaged 42 ppm, more than five times the 7 ppm averaged by the TCA. Manganese concentrations were significantly higher for runs with oxidation than for runs without oxidation, probably because $MnSO_3$ is insoluble.

21.2.4 Molybdenum (Mo)

The average concentration of molybdenum was exactly the same, 5 ppm for both systems. Molybdenum concentrations averaged 1 ppm for low fly ash runs and 5 ppm for high fly ash runs.

21.2.5 Nickel (Ni)

The average concentrations were higher in the venturi than in the TCA and seemed to follow trends similar to manganese, where concentrations were higher for runs with oxidation. The most probable explanation is that nickel sulfite is insoluble and the sulfate is soluble.

21.2.6 Titanium (Ti)

Measured concentrations of titanium were relatively low (less than 0.5 ppm) and invariant.

21.2.7 Vanadium (V)

Higher concentrations of vanadium were recorded in the TCA (1.5 to 2 ppm), with lower pH and no oxidation, than in the venturi (about 1 ppm).

21.3 NITROGEN OXIDES AND TOTAL ORGANIC CARBON

When the trace metals analysis program was initiated, it was decided that the study should include the analysis of other chemical species that could inhibit sulfite oxidation. Two classes of compounds present in the scrubber environment that could contribute to such an effect are nitrogen oxides (NO_x) and organic carbon compounds.

The concentration of nitrogen oxides in the venturi averaged 45 ppm, three times the 15 ppm recorded for the TCA. The tighter material balance of the venturi is the most likely explanation for this.

Total organic carbon levels measured for both scrubbers and the raw water were relatively low and invariant, usually less than 6 ppm.

21.4 FLUE GAS OXIDANT MONITORING PROGRAM

Nitrogen oxide (NO) and oxygen (O_2) in the flue gas were analyzed for two weeks during October 1976. Data collection was limited due to difficulties with equipment and calibration problems. NO concentrations were measured at about 400 ppm (± 50 ppm) for both systems. No other data were obtained from this program.

21.5 SUMMARY

The primary purpose for initiating the analysis program for trace metals, nitrogen, and organic carbon was to attempt to identify those constituents of the scrubber environment which might have an effect on sulfite oxidation. No oxidation excursions occurred during this period, and thus no results toward that end were obtained. However, the data obtained have significantly contributed to an understanding of scrubber chemistry, particularly with regard to the effects of pH. Continued routine analysis of the slurry liquor will be performed for both systems, and the results will be reported in future publications.

Section 22

WASTE SOLIDS DEWATERING AND CHARACTERIZATION

The results of slurry solids dewatering tests at the Shawnee Test Facility are presented in this section. These tests were done to monitor operation of the dewatering equipment and to evaluate the settling and dewatering characteristics of the discharge slurries.

The testing of two types of dewatering equipment is discussed. First, the results of field testing of an inclined plate settler, the Lamella Gravity Settler by Parkson Corporation, are presented; then, the results of tests using a hydroclone as a means of separating gypsum from unreacted alkali and sulfite are given. The hydroclone used was the Dorrclone P50A by Dorr-Oliver.

Results are given for routine cylinder settling and funnel filtration tests performed during this reporting period on both the venturi/spray tower and TCA systems. Also presented are filter leaf test results on slurries obtained from tests with and without forced oxidation.

Two methods for characterizing the particle size distribution of slurry solid were tested: the hydrometer method and pipette method. These tests were applied to oxidized slurries and also to slurry streams separated in the hydroclone testing.

Scanning electron micrographs (SEM) were taken of various slurries to determine whether any significant particle size changes had occurred during various testing operations.

Finally, a study of gypsum crystallization was done to determine the extent to which discharged solids could be improved by increasing the crystal size and reducing the fines content.

22.1 THE LAMELLA GRAVITY SETTLER THICKENER TEST PROGRAM AND RESULTS

Testing of a Lamella inclined plate settler, a compact sludge dewatering device manufactured by the Parkson Corporation, was conducted at the Shawnee Test Facility from July through November 1977. The tests were designed to determine the maximum clarification and thickening capacity of the unit under different test run conditions, such as the type of slurry feed, the feed rate, and the addition of flocculant. Potential fouling problems were also identified.

22.1.1 Equipment Description

The Lamella Gravity Settler Thickener, Parkson Unit LGST No. 3, was 20 feet tall and consisted of two tanks constructed of 316 stainless steel. The upper rectangular tank was a high-rate gravity settler and contained a series of parallel FRP Lamella plates inclined at 55 degrees (plate pack). The lower circular tank was 4 feet in diameter and 10 feet in height and served as the thickener; it contained a picket fence type sludge rake and an underflow outlet. The total liquid capacity was approximately 1,000 gallons.

Each of the inclined plates in the plate pack had an equivalent settling area equal to its projection onto a horizontal plane. Each square foot of this projected area was equal in settling capacity to a square foot of area in a conventional settler. The unit being tested had a total settling area of 115 ft^2, 57.5 ft^2 of which was utilized as clarification area.

The settler thickener is shown in Figure 22-1. The slurry enters from a bottomless feedbox into the plate pack from the side, about halfway from the bottom of the plate. Liquor flows upward, exiting at the top of the rectangular tank through flow distribution orifices. This forces the slurry to be evenly distributed over all of the plates. The solids settle out onto the plate surfaces and slide downward into the circular thickening tank. The thickened sludge is then pumped out of the unit via a Moyno underflow pump.

22.1.2 Test Plan

A series of tests involving the Lamella Settler was completed using the following: lime or limestone slurry, flue gas with low or high fly ash loading, and oxidized or unoxidized slurry. The aim of the tests was to determine for each type of slurry the maximum possible feed rate that would maintain the underflow solids concentration at greater than 40 weight percent and the overflow at less than 0.5 weight percent. Additionally, the solids concentration profile in the Lamella circular hold tank as a function of feed rate was measured. Frequency of plugging of the plates and lines and the amount of maintenance needed were also noted.

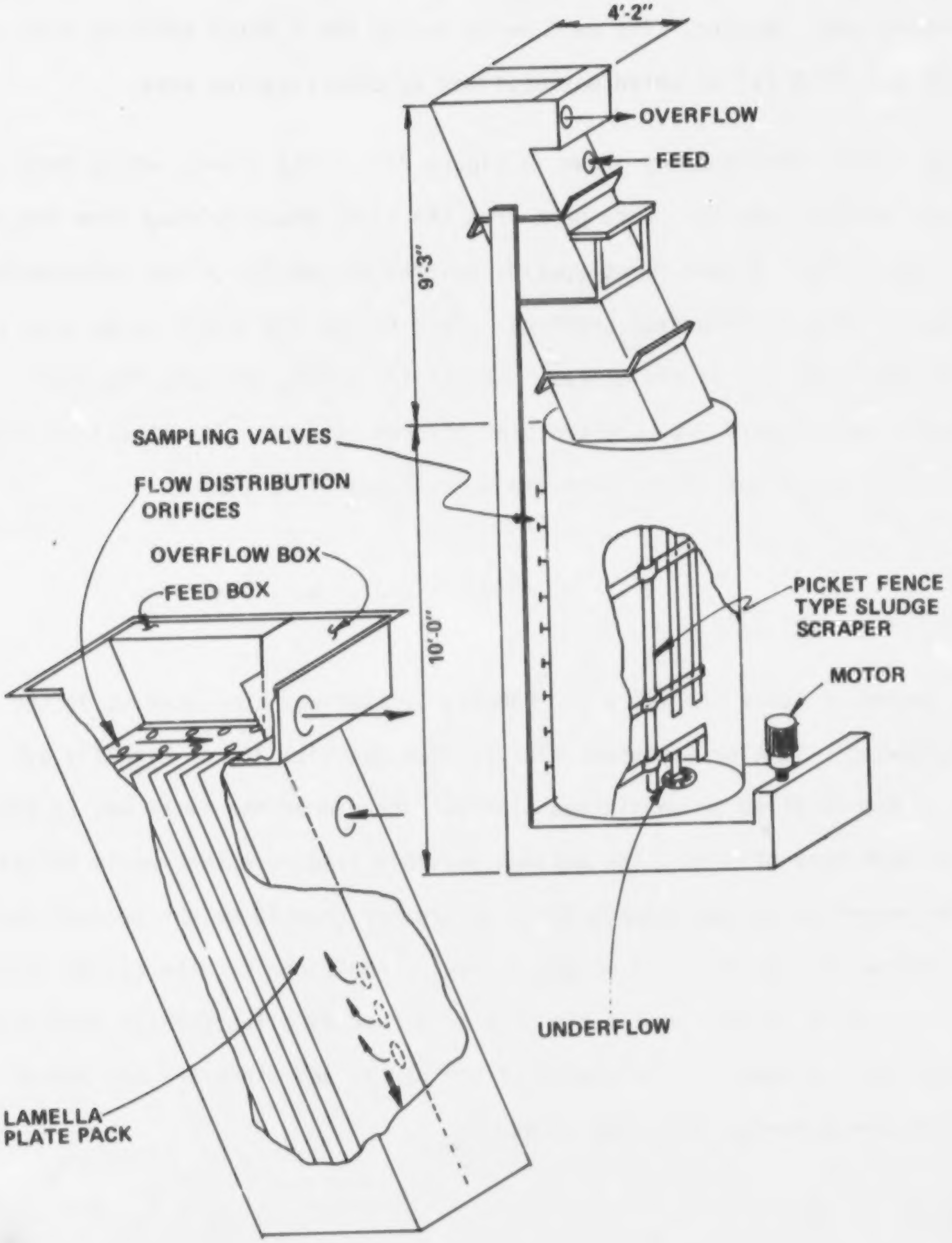

4'-2"
OVERFLOW
FEED
9'-3"
SAMPLING VALVES
FLOW DISTRIBUTION ORIFICES
OVERFLOW BOX
FEED BOX
10'-0"
PICKET FENCE TYPE SLUDGE SCRAPER
MOTOR
UNDERFLOW
LAMELLA PLATE PACK

Figure 22-1. The Lamella Gravity Settler Thickener

22.1.3 Size Comparison of a Lamella Settler and a Conventional Clarifier

A comparison of the Lamella Settler with a conventional clarifier of equivalent settling area, based on land requirements, shows that a Lamella Settler requires about one-sixth the land area needed for an equivalent conventional clarifier.

The capacity test data from the Lamella Settler with oxidized slurry having high fly ash loading was used for scaleup from the 10-MW Shawnee Test Facility. Sizing estimates showed that 5,200 ft^2 of settling area would be required for a 500-MW plant. This is equivalent to an 80-ft diameter conventional clarifier which requires 5,200 ft^2 of land area. Based on size estimates obtained from the Parkson Corporation, the manufacturers of the Lamella Settler, a Lamella Settler Model 10400/55 with a 5,200 ft^2 settling area should require only 800 ft^2 of land area, a savings of 4,400 ft^2 over a conventional clarifier.

22.1.4 Summary of Tests

Below is a summary of the testing of the Lamella Settler, indicating the type of slurry used, the run number, and the dates of the testing. In subsequent subsections, major conclusions of the testing are discussed. Data from the tests are presented in Appendix L.

Slurry Type	Subsection	Runs	Dates of Test
Oxidized limestone high fly ash loading 15 weight percent solids	22.1.4.1	803-2A & 804-2A 818-1A 819-1A	July 12 - July 20 Oct. 26 - Oct. 31 Oct. 31 - Nov. 29
Oxidized lime low fly ash loading 15 weight percent solids	22.1.4.2	859-1A	July 26

Oxidized limestone low fly ash loading 15 weight percent solids	22.1.4.3	809-1A	Aug. 15 - Aug. 17
Unoxidized limestone high fly ash loading 8 & 15 weight percent solids flocculant testing	22.1.4.4	714-2A 714-2B	Aug. 31 - Sept. 9
Oxidized lime high fly ash loading 8 & 15 weight percent solids flocculant testing	22.1.4.5	862-1A	Oct. 13 - Oct. 18
Unoxidized limestone high fly ash loading 15 weight percent solids	22.1.4.6	717-2A	Oct. 21 - Oct. 24

22.1.4.1 Oxidized limestone slurry with high fly ash loading

Several tests were done with this type of slurry during Runs 803-2A, 804-2A, 818-1A, and 819-1A.

- During Runs 803-2A and 804-2A, a feed rate of 17 gpm gave an overflow solids concentration of 0.32 weight percent (compared to less than 0.1 weight percent normally obtained for the TCA clarifier) and an underflow of 38 weight percent. However, at feed rates of 20 to 22 gpm, the overflow solids concentrations were 0.82 and 1.9 weight percent, respectively, exceeding the desired value of 0.5 weight percent or less. At the end of the testing, the entire unit was found to be clean except for minor soft solids in the weir box.

- A cylinder settling test on slurry from Run 818-1A indicated that 80 gpm would be the maximum feed rate to the Lamella Settler overflow solids. However, 20 gpm was the highest feed rate that yielded satisfactory overflow solids of 0.3 to 0.6 weight percent. Feed rates of 21.5 and 24 gpm had overflow solids of 0.8 and 1.2 weight percent, respectively. The underflow solids concentration at 20 gpm was 34 to 57 weight percent.

- Slurry from Run 819-1A at a feed rate of approximately 9 gpm yielded satisfactory results in this one-month reliability test. The overflow solids concentration varied from 0.05 to 0.18 weight percent. The underflow solids varied from 35 to 54 weight percent.

- Throughout the test, the Lamella Settler operated smoothly; there were no plugging problems or erratic behavior. Visual inspection revealed that there was no scale buildup.

22.1.4.2 Oxidized lime slurry with low fly ash loading

- With slurry from Run 859-1A at a feed rate of 10 gpm, the underflow line plugged. This plugging was due to the high settling rate of the essentially pure gypsum particles. To remedy this problem, the diameter of the underflow line was increased and a freshwater purge line was added.

22.1.4.3 Oxidized limestone slurry with low fly ash loading

- With slurry from Run 809-1A at a feed rate varying from 6 to 12 gpm, the overflow solids remained below 0.5 weight percent, ranging from 0.07 to 0.45 weight percent. The underflow solids varied from 28 to 41 weight percent.

- Throughout the testing, the settler performed well, with only minor plugging of the underflow line. This plugging was corrected by water purging the line.

22.1.4.4 Unoxidized limestone slurry with low fly ash loading

Both laboratory cylinder settling tests and Lamella Settler tests were done on slurry from Run 714-2A and Run 714-2B. Laboratory cylinder settling tests on both 15 and 8 weight percent slurries were done with the addition of 0 to 25 ppm flocculant, American Cynamid's Superfloc 1204, and Nalco's nontoxic flocculant, Nalco 8861. Subsequently, the Lamella Settler was run with slurries containing 8 weight percent solids without flocculant. The following results were obtained.

- For 15 weight percent unflocculated slurry, the maximum feed rate to the Lamella Settler for satisfactory overflow was 2 gpm.
- For 8 weight percent slurry flocculated with Nalco 8861, the maximum feed rate to the Lamella Settler for satisfactory overflow was 44 gpm, though this may have been influenced by the limiting capacity of the underflow pump (about 7 gpm).
- With no flocculant addition, slurries with 8 weight percent solids had a higher mass loading than 15 weight percent slurries (2.7 to 5.7 times as great). This was a result of less hindered settling in the more dilute slurry.
- The increase in mass loading rates of 15 weight percent slurries by flocculant addition was small (1.5 to 2.5 times as great).
- The increase in mass loading rates of 8 weight percent slurries by flocculant addition was large (28 times as great).
- Nalco 8861 had a greater effect on mass loading rate of 8 weight percent slurry than the Superfloc 1204 (3.3 to 4.1 times more effective).
- Visual inspection of the Lamella Settler showed that the system was free of solids buildup.

22.1.4.5 Oxidized lime slurry with high fly ash loading

- A laboratory cylinder settling test for this slurry with no flocculant addition at 15 weight percent solids, from Run 862-1A, indicated that the maximum feed rate to the Lamella Settler would be 10.2 gpm.

- Slurry of 15 weight percent solids with no flocculant addition at a feed rate of 10 gpm gave a satisfactory overflow of 0.07 to 0.51 weight percent solids. The underflow was 34 to 49 weight percent solids.

- A laboratory cylinder settling test of this slurry with 9 ppm Nalco 8861 flocculant and diluted to 8 weight percent indicated the maximum feed rate to be 40 gpm.

- Slurry of 8 weight percent solids with Nalco 8861 addition at a feed rate of 40 gpm gave overflow solids of 0.03 to 0.07 weight percent and underflow solids of 41 to 52 weight percent.

22.1.4.6 Unoxidized limestone slurry with high fly ash loading

- With slurry from Run 717-2A at 15 weight percent solids, a cylinder settling test indicated a maximum feed rate of 2.3 gpm.

- In a test at 2.3 gpm feed rate, the solids concentration of the overflow increased steadily from 0.6 to 6.8 weight percent during the run. This run was originally intended for a long-term Lamella reliability run. However, the run was discontinued because of the high solids in the overflow and the inability of the pump to control flow below 2 gpm.

22.1.5 Solids Concentration Profiles

Solids concentration profiles in the Lamella Settler circular hold tank were determined throughout the testing by taking side drawoff samples at nine levels on the tank. The profiles for all the tests were fairly uniform. The data are summarized in Appendix L.

Generally, the concentration profile was uniform and similar to the inlet solids concentration for the oxidized slurry, and was uniformly near the underflow concentration for the unoxidized slurry. It is postulated that the oxidized slurry solids settle quickly and thus do not have sufficient time to diffuse across the thickener tank to the sampling valves, whereas the unoxidized slurry solids settle slowly and consequently and have a better chance of diffusing across the thickener tank to the sampling valves.

22.1.6 Conclusions

- The Lamella Settler compared with a conventional clarifier of equivalent settling area requires about one-sixth the land area, and has correspondingly smaller slurry inventory.
- Oxidized slurry at 15 weight percent solids has mass loading rates anywhere from 5 to 10 times that of unoxidized slurry.
- Flocculant addition greatly increased the mass loading rate of both oxidized and unoxidized slurry.
- After initial modifications the Lamella Settler operated free from plugging, scaling, and mechanical problems.
- In comparison to conventional clarifiers, the Lamella Settler is superior for clarification but does not appear to offer an advantage for thickening.

22.2 CYLINDER SETTLING AND FUNNEL FILTRATION TESTS

Cylinder settling tests and funnel filtration tests were conducted on a routine basis to monitor the dewatering characteristics of the slurries and to detect any gross changes. The initial settling rate indicates the rate at which the solids fall during the unhindered portion of settling. Ultimate settled solids represent the highest achievable solids concentration in a thickener or settling pond. Funnel test cake solids represent those achievable on a filter type dewatering device.

Data for the period from January 1977 through May 1978 are presented in Appendix L, including alkali type, fly ash loading, pH, and MgO addition. Results from earlier test blocks are presented in the Third Progress Report (Reference 4).

Table 22-1 summarizes the settling data obtained, including the effect of oxidation, fly ash loading, alkali, and additive concentration on initial settling rate, ultimate settled solids, and funnel test cake solids.

The results during the testing period are similar to previous results. The benefits of forced oxidation on the settling and dewatering characteristics of the sludge are clearly evident. For runs without MgO addition, the initial settling rate for an oxidized slurry (0.7 to 1.2 cm/min average range) was much higher than for unoxidized slurry (0.2 to 0.4 cm/min average range), regardless of whether the slurry had high or low fly ash loading. Again excluding magnesium runs, the average ultimate settled solids and funnel test solids ranged from 70 to 76 weight percent for the oxidized slurry, whereas for unoxidized slurry they ranged from 40 to 57 weight percent.

The initial settling rate of unoxidized slurry is probably limited by the sulfite particles. In the case of oxidized slurry, the rate is probably limited by the fly ash. Even in the case of slurry with low fly ash loading, fly ash constitutes about one weight percent of the solids.

The addition of magnesium primarily affected the initial settling rate. For oxidized slurry with the two-loop mode of oxidation and with 8000 ppm effective magnesium ion concentration, the average initial settling rate, the ultimate settled solids concentrations and the funnel test cake solids concentrations were all slightly lower than those for oxidized slurry without magnesium.

Table 22-1

SUMMARY OF DEWATERING CHARACTERISTICS OF SHAWNEE SYSTEM BLEED

Oxidation	Fly Ash Loading	Alkali	Oxidation Mode	Initial Settling Rate, cm/min		Ultimate Settling Solids, wt%		Funnel Test Cake Solids, wt%		Slurry Solids	Effective Mg^{++} Concentration, ppm
				Avg.	Range	Avg.	Range	Avg.	Range		
Yes	High	LS	1-loop	1.1	0.6-1.3	74	67-84	76	73-80	15	0
Yes	High	LS	2-loop	1.2	1.0-1.4	72	62-86	72	65-88	15	0
Yes	High	LS	Bleed Stream	0.4	0.3-0.6	71	61-84	73	71-76	15	5000
Yes	High	LS	2-loop	0.8	0.2-1.2	66	46-73	70	46-76	15	8000
Yes	High	L	2-loop	1.0	0.8-1.2	73	61-85	71	64-78	15	0
Yes	Low	LS	2-loop	0.9	0.6-1.2	74	61-87	73	64-82	15	0
Yes	Low	L	2-loop	1.2	0.4-2.4	70	60-81	76	64-83	15	0
No	High	LS	-	0.2	0.1-0.5	54	41-67	57	48-66	15	0
No	High	LS	-	0.2	0.1-0.4	45	30-60	57	45-64	15	5000
No	High	LS	-	0.1	0.0-0.1	41	32-46	55	47-69	15	9000
No	High	L	-	0.2	0.2-0.5	50	48-66	53	51-55	15	0
No	High	L	-	0.8	0.2-1.2	42	31-52	52	43-63	8	2000
No	Low	LS	-	0.2	0.1-0.5	43	33-54	50	41-59	15	0
No	Low	L	-	0.4	0.1-0.9	40	30-55	45	40-50	8	0

Note: Values for forced oxidation runs are only from data where solids oxidation is greater than or equal to 90 percent.

For bleed stream oxidized slurry, the initial settling rate was about half that of other oxidized slurries. The ultimate amount of settled solids and funnel test cake solids were in the same range as with other oxidized slurries.

For unoxidized slurry, the effect of magnesium was more pronounced. For a limestone slurry with high fly ash loading, the average initial settling rate was 0.20 cm/min with no magnesium and 0.05 cm/min with 9000 ppm magnesium, a decrease of a factor of four. The amount of ultimate settled solids was somewhat lower for the slurries with magnesium; the amount of funnel test cake solids was about the same.

One factor affecting the initial settling rate but not the ultimate amount of settled solids when magnesium is present is the increase in liquor viscosity and density due to the increased total dissolved solids.

22.3 FILTER LEAF TESTS

Bench-scale filter leaf tests were conducted to identify promising filter cloths for future evaluation on the rotary drum filter and to determine the filtration characteristics of sludges generated under different operating conditions.

All tests were conducted with a standard filter leaf having a cloth area of 0.10 ft^2. Rotary drum filter operation was simulated by immersing the filter leaf, under vacuum, into gently agitated slurry for a time equivalent to the filter cake form time and then removing the leaf from the slurry and draining it under vacuum for an equivalent filter cake drying time.

22.3.1 Cloth Evaluation Tests

Samples of 23 cloths and three previously blinded ones (saved after removal from the drum filter) were evaluated by a filter leaf procedure designed to simulate the Shawnee drum filter operating at about one rpm with a submergence (area basis) of 33 percent. The 60-second complete filtration cycle was divided into 20 seconds for cake form time, 34 seconds of drying time, and 6 seconds of cake discharge time. No attempts were made to adjust cycle time to optimize individual cloth performance.

A summary of the cloth properties is presented in Table 22-2. The cloths had an air permeability range of 0.8 to 100 cfm/ft^2 (air permeability is defined as the air flow through the cloth, in cfm/ft^2, under a pressure differential of 1/2 inch H_2O across the cloth). Evaluations were carried out on two types of unoxidized clarifier underflow slurry with an initial solids concentration of 20 weight percent: lime slurry with high fly ash loading from Run VFG-1P (see Table 22-3) and limestone slurry with low fly ash loading from Run 706-2A (see Table 22-4). Cloths numbered 8, 11, and 14 were of the types normally used on the Shawnee rotary drum filter. None of the other cloths tested showed significantly improved dry cake production rate or cake solids concentration.

For the lime slurry with fly ash, the filtrate rate increased with air permeability (see Figure 22-2) up to a maximum filtrate rate of 53 gal/hr-ft^2 for cloths with permeability of 40 cfm/ft^2 or higher. Cake production ranged from 73 to 116 lb/hr-ft^2, generally increasing with cloth permeability. For the limestone slurry without fly ash, filtrate rate (35 to 45 gal/hr-ft^2) and cake production (92 to 145 gal/hr-ft^2) were both independent of cloth type, indicating that cloth resistance was overshadowed by cake resistance.

Table 22-2
CLOTH PROPERTIES

Cloth Number	Vender[1]	ID Number	Air Permeability, cfm/ft^2	Material	Weave	Yarn	Thread Count	Cloth Finish	Cloth Weight ounces/yd^2
1	E	NY-317F	0.8	Nylon	2/2 Twill	multi-filament	220 x 128	Heat Set	3.8
2	E	POPR-925F	1.0	Polypropylene	2/1 Basket	multi-filament	104 x 34	Heat Set	8.0
3	A	STE-GODO-AJO	2.9	Olefin	1/1 Plain	multi-filament	60 x 30	--	9.0
4	L	0-2107	3.0	Polypropylene	Plain	--	48 x 26	Scoured/Heat Set	14.0
5	E	NY-330	3.2	Nylon	--	--	--	--	--
6	A	XB-HG6D4A-J8	5.0	Polyester	1/1 Plain	multi-filament	66 x 34	--	9.8
7	E	NY-384F	6.0	Nylon	1/1 Plain	multi-filament	79 x 40	Heat Set	9.0
8[2]	TFI	9162	7.0	Polypropylene	Plain	multi-filament	59 x 32	--	8.0
9	A	WNH-G2E7-AG8	7.5	Nylon	1/1 Plain	multi-filament	62 x 47	--	6.8
10	E	POPR-851	8.3	Polypropylene	1/1 Plain	multi-filament	58 x 32	Greige	8.0
11[2]	L	7512-SHS	10.0	Polypropylene	Plain	--	58 x 28	Scoured/Heat Set	8.5
12	A	ST-EF8D8A-G1	10.0	Olefin	1/1 Plain	multi-filament	58 x 38	--	6.1
13	E	NY-304	14.0	Nylon	1/1 Plain	spun staple	54 x 28	Grey	11.6
14[2]	A	STE-F9D8-HJO	20.0	Olefin	2/2 Twill	multi-filament	58 x 38	--	9.0
15	A	WNG-NOG6-PH3	24.0	Nylon	1/4 Satin	multi-filament	130 x 66	--	8.3
16	A	XBH-H4G8-IFO	24.0	Polyester	3/1 Twill	multi-filament	74 x 68	--	5.0
17	E	POPR-873	30.0	Polypropylene	1/1 Plain	mono-filament	116 x 34	Calendered	6.2
18	E	POPR-852F	32.5	Polypropylene	2/2 Twill	multi-filament	64 x 34	Heat Set	9.3
19	E	NY-529F	39.65	Nylon	2/2 Twill	multi-filament	144 x 54	Heat Set	8.0
20	L	4048-SHS	40.0	Polyester	Twill	--	156 x 60	Scoured/Heat Set	9.2
21	A	ST-EF8E6H-G2	48.0	Olefin	2/2 Twill	multi-filament	58 x 46	--	6.2
22	E	PO-801HF	50.0	Polyethylene	1/1 Plain	mono-filament	112 x 48	Heat Set	11.0
23	E	POPR-859	100.0	Polypropylene	2/2 Twill	mono-filament	68 x 30	Greige	8.5

(1) E = Eimco, A = Ametek, L = Lamport, TFI = Technical Fabricators.

(2) Sample of cloth normally used on the rotary drum filter.

Table 22-3

FILTER LEAF TEST RESULTS ON LIME SLURRY WITH HIGH FLY ASH LOADING(5)

Cloth Number(1)	Air Permeability, cfm/ft^2	Dry Cake Production, lb/ft^2-hr(4)	Filtrate Rate, gal/ft^2-hr(4)	Cake Thickness, in.	Cake Solids, wt%	Filtrate Solids, wt%
1	0.8	74	35	1/4	65.6	0.00
2	1.0	79	33	1/4	57.7	0.01
3	2.9	78	32	1/4	60.1	0.01
4	3.0	75	35	1/4	64.8	0.01
5	3.2	73	37	1/4	66.6	0.01
6	5.0	75	43	1/4	64.0	0.05
7(3)	6.0	74	32	1/4	65.6	0.02
8	7.0	73	46	1/4	66.9	0.01
9	7.5	111	46	3/8	65.1	0.02
10(3)	8.3	116	46	3/8	59.1	0.10
11	10.0	98	42	5/16	61.8	0.02
12	10.0	110(2)	48(2)	3/8(2)	64.8(2)	0.03(2)
13(3)	14.0	--	--	--	--	--
14	20.0	112	51	3/8	64.6	0.03
15	24.0	101	56	11/32	66.0	0.13
16	24.0	113	44	3/8	63.7	0.01
17	30.0	92	51	5/16	66.5	0.27
18	32.5	95	49	5/16	62.3	0.07
19	39.65	94	53	5/16	63.4	0.11
20	40.0	110	52	3/8	66.4	0.14
21	48.0	112	52	3/8	64.6	0.23
22	50.0	111	56	3/8	66.0	0.25
23	100.0	111	52	3/8	65.9	0.36

1. Refer to Table 22-2.
2. Ran cloth on limestone slurry only.
3. Sample of cloth normally used on the rotary drum filter.
4. Based on a sixty-second cycle.
5. From Run VFG-1P.

Table 22-4

FILTER LEAF TEST RESULTS ON LIMESTONE SLURRY WITH LOW FLY ASH LOADING(6)

Cloth Number(1)	Air Permeability, cfm/ft^2	Dry Cake Production, lb/ft^2-hr(5)	Filtrate Rate, gal/ft^2-hr(5)	Cake Thickness, in.	Cake Solids, wt%	Filtrate Solids, wt%
1	0.8	145	36	5/8	48.0	0.00
2	1.0	131	39	5/8	43.2	0.02
3	2.9	92	36	7/16	43.4	0.07
4	3.0	106	40	1/2	44.0	0.02
5	3.2	-- (2)	-- (2)	-- (2)	-- (2)	-- (2)
6	5.0	105	37	1/2	43.7	1.20 (3)
7	6.0	104	41	15/32	45.8	0.05
8 (4)	7.0	108	38	1/2	44.6	0.25 (3)
9	7.5	92	35	7/16	44.5	0.01
10	8.3	106	44	1/2	43.9	0.77 (3)
11 (4)	10.0	108	41	1/2	44.7	0.10
12	10.0	114	45	9/16	41.6	0.03
13	14.0	102	45	1/2	42.1	0.00
14 (4)	20.0	134	41	5/8	45.3	0.03
15	24.0	109	39	1/2	44.9	0.01
16	24.0	99	44	1/2	41.0	0.03
17	30.0	135	42	5/8	44.6	0.06
18	32.5	133	39	5/8	43.9	0.07
19	39.65	92	39	7/16	43.1	0.05
20	40.0	107	40	1/2	44.2	0.02
21	48.0	116	38	17/32	45.2	0.09
22	50.0	121	38	9/16	45.4	0.07
23	100.0	119	43	9/16	43.9	0.84 (3)

1. Refer to Table 22-2.
2. Ran cloth on lime slurry only.
3. Leak suspected during leaf test.
4. Sample of cloth normally used on the rotary drum filter.
5. Based on a sixty-second cycle.
6. From Run 706-2A.

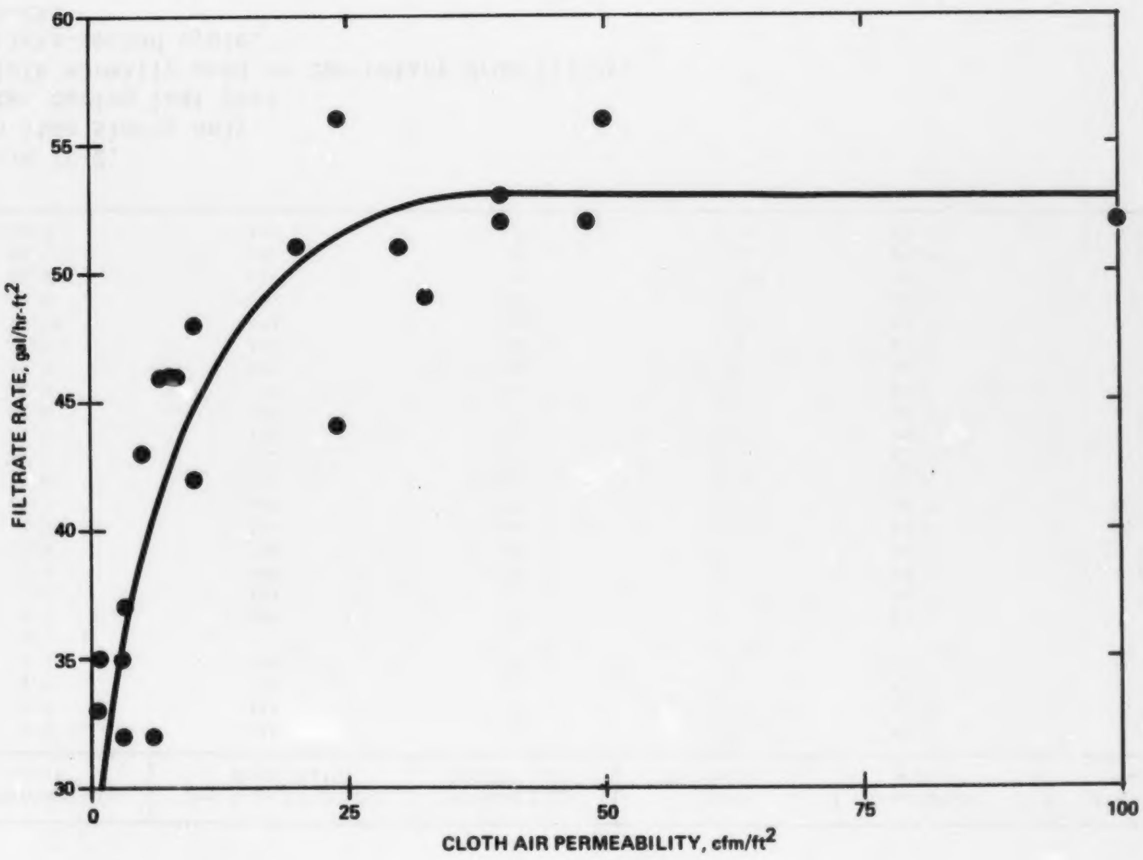


Figure 22-2. Filter Leaf Filtrate Rate versus Cloth Air Permeability, Lime with Fly Ash Slurry (60 second cycle)

Weight percent solids in the filtrate gradually increased with increasing cloth permeability from 0.00 to 0.36 for lime and from 0.00 to 0.09 for limestone. However, all of these values are within the acceptable operating range. High filtrate solids values with limestone for cloths 6, 8, 10, and 23 were attributed to leakage during these particular tests.

Tests with previously blinded cloths of types 8, 11, and 14 showed a reduction in cake production rate to between 25 and 75 percent of the clean rate (see Table 22-5).

22.3.2 Filtration Tests

Additional filter leaf tests were performed at Shawnee to evaluate the filtration characteristics of sludge generated during the following types of operation:

Alkali	Fly Ash Loading	Forced Oxidation	Independent Scrubber Loops
Lime	High	Yes	2
Lime	Low	Yes	2
Lime	Low	No	---
Limestone	High	Yes	1
Limestone	High	Yes	2

Results of tests at the optimum filtration cycle for each type of operation are presented in Table 22-6. Note that results for slurries from forced-oxidation tests were similar, regardless of alkali, fly ash content, or number of scrubber loops. Oxidized cake solids were between 70 and 80 weight percent and dry solids

Table 22-5

FILTER LEAF TEST RESULTS WITH BLINDED CLOTHS

LIME SLURRY WITH HIGH FLY ASH LOADING

Cloth Number(1)	Total Operating Hours	Dry Cake Production, lb/ft^2-hr(2)		Filtration Rate, gal/ft^2-hr(2)		Cake Solids, wt%	
		New	Blinded	New	Blinded	New	Blinded
8	866	73	21	46	8	66.9	57.6
11	349	98	40	42	27	61.8	67.1
14	530	112	--	51	--	64.6	--

LIMESTONE SLURRY WITH LOW FLY ASH LOADING

Cloth Number(1)	Total Operating Hours	Dry Cake Production, lb/ft^2-hr(2)		Filtrate Rate, gal/ft^2-hr(2)		Cake Moisture, wt%	
		New	Blinded	New	Blinded	New	Blinded
8	866	108	56	38	21	44.6	42.5
11	349	108	88	41	29	44.7	44.6
14	530	134	43	41	29	45.3	43.0

(1) Refer to Table 22-2.

(2) Based on a sixty-second cycle.

Table 22-6

FILTER LEAF TEST RESULTS AT OPTIMUM FILTRATION CYCLE

Alkali Type	Fly Ash Loading	Forced Oxidation	Scrubber Loops	Form Time, sec	Dry Time, sec	Cycle Time, sec	Initial Solids, wt.%	Cake Solids, wt.%	Cake Thickness, in.	Dry Solids Loading, lb/ft^2-hr	Filtrate Loading, gal/ft^2-hr	Submergence, % of cycle
Lime	High	Yes	2	5	25	40	58.4	82.3	3/4	428	27.3	12.5
Lime(1)	Low	Yes	2	5	20	33	47.9	70.1	3/8	295	23.3	30.0
Lime(1)	Low	No	--	5	20	33	39.3	49.9	3/8	281	18.1	30.0
Limestone	High	Yes	1	5	25	40	58.9	79.8	7/16	258	14.7	12.5
Limestone	High	Yes	2	5	30	47	52.7	78.8	5/16 - 7/16	212	16.0	21.0

(1) Worst results of several runs at optimum filtration cycle for this slurry.

loadings were between 200 and 300 lb/hr-ft^2, except for the high value of 428 lb/hr-ft^2 for two-loop forced oxidation with lime and high fly ash loading.

The unoxidized lime solids with low fly ash loading had much lower cake solids content (about 50 weight percent). Appendix L presents detailed filter leaf test results.

22.4 HYDROMETER AND PIPETTE PARTICLE SIZE DISTRIBUTION TESTS

One of the methods used to assess the ease of solids dewatering is to test the initial settling rate of solid particles within the slurry. However, the product solids at Shawnee are a mixture of $CaSO_4 \cdot 2H_2O$, $CaSO_3 \cdot 1/2H_2O$, fly ash, unreacted lime or limestone, and other inert materials. All have independent particle size distributions which superimpose to form the particle size distribution of the slurry mixture. The use of settling rate data to assess the effects of process variables on the $CaSO_4 \cdot 2H_2O$ particle size distribution generated during forced-oxidation testing can be masked by other materials in the slurry, particularly fly ash. Even in operations with flue gas having passed through the electrostatic precipitators at Shawnee, enough fly ash gets past the precipitator to form about one weight percent of the product solids.

This fly ash is extremely fine when compared with $CaSO_4 \cdot 2H_2O$ particles, and settles at a slower rate. The resulting limited settling rate limit appears to be 1.5 to 2.5 cm/min at the Shawnee Test Facilty. Once the gypsum settling rate reaches this limit, any increase in the average size of gypsum particles due to changes in process variables will not be observed. Therefore, a test to assess process variable effects on gypsum particle size in the presence of fly ash is needed.

Two particle size analysis tests potentially capable of assessing gypsum particle sizes in the presence of fly ash were briefly investigated: the hydrometer test and the pipette test. The hydrometer test was ASTM designation D422-63 (Reapproved 1972), "Standard Method for Particle - Size Analysis of Soils". In this test, a liter of solution containing about 50 grams of gypsum solids is placed in a 1-liter graduated cylinder in which an ASTM hydrometer (151H or 152H in ASTM Specification E100) is placed. The hydrometer reading is observed with time of settling to give the particle size distribution of the solids, which range in size from 5 to 75 microns. This technique is used as a regular laboratory analysis by the Bechtel Pipeline Division Slurry Laboratory.

Two samples from forced-oxidation testing were analyzed by the ASTM hydrometer method: one from Run 857-1A and one from Run 858-1A (both runs with low fly ash loading). The hydrometer test size distributions obtained from the two samples are plotted in Figure 22-3 (as circles). Over the size range measured, no significant difference between the two size distributions is noticeable. Even though the flue gas in these runs had passed through an electrostatic precipitator, fly ash was visibly present in the slurry.

To identify which particle species was falling most rapidly (i.e., fly ash or $CaSO_4 \cdot 2H_2O$), a pipette sampling method was used (Reference 10). The pipette method does not involve the use of a hydrometer. Instead a 10-ml pipetted sample is periodically removed from the settling slurry at some constant depth. The sample is analyzed for weight of solids and weight percent $CaSO_4 \cdot 2H_2O$. From this information and Stokes' Law, the corrected $CaSO_4 \cdot 2H_2O$ particle size

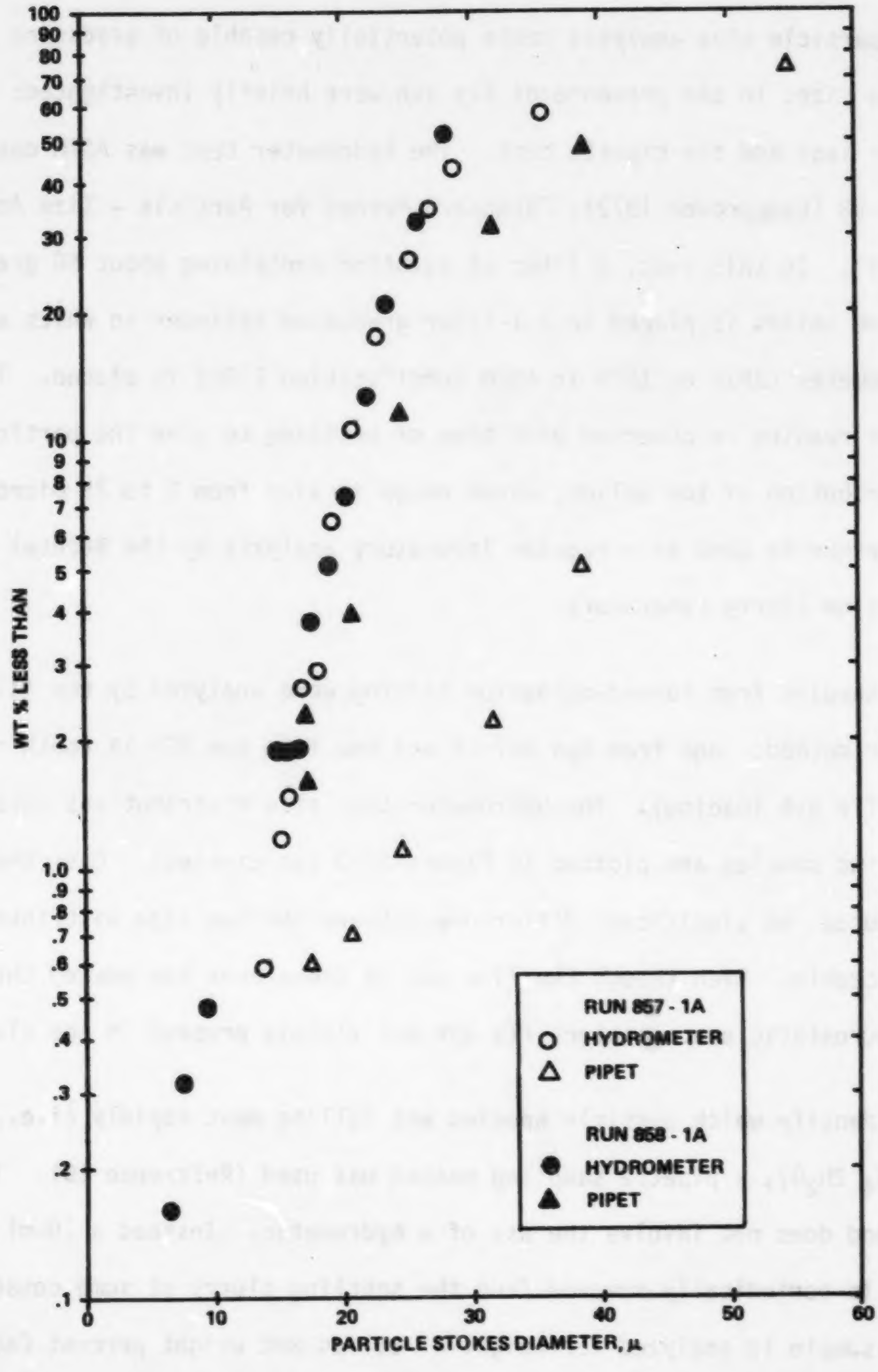


Figure 22-3. Particle Size Distributions of Oxidized Slurry with Low Fly Ash Loading from the Venturi/Spray Tower System

distribution can be calculated.

The overall size distributions from the pipette size distribution test are also plotted in Figure 22-3 (as triangles). Agreement between methods was good for Run 858-1A but not for Run 857-1A. This may have been caused by the poor sampling technique associated with the pipette method.

The data from the pipette test are much more revealing when weight percent $CaSO_4 \cdot 2H_2O$ from each sample is plotted along with the overall size distribution. This has been done for a sample from Run 857-1A in Figure 22-4 and a sample from Run 858-1A in Figure 22-5. These plots illustrate that the fines are mostly ash (e.g., only 6 percent of the solids smaller than 17 microns are $CaSO_4 \cdot 2H_2O$ in Figure 22-4, and if the two plots were combined a $CaSO_4 \cdot 2H_2O$ size distribution could be generated).

Static cylinder settling tests of the two slurries were run after they were both adjusted to the same initial percent solids with clarified liquor. Both the upper and lower interfaces observed in these settling tests are plotted in Figure 22-6. Chemical analysis showed that the solids built up from the bottom of the cylinder (the lower interface) were gypsum and that the solids settling from the top (the upper interface) were essentially fly ash. This is further proof that the initial settling rates presented for slurry from the forced-oxidation tests normally represent the size distribution of the fly ash and not the size distribution of the $CaSO_4 \cdot 2H_2O$ solids.

The data from these comparisons prove that the initial settling rate test is not a valid indication of the relative size distribution of the gypsum crystals generated during forced-oxidation testing. The hydrometer test gives a good indication of the overall size distribution but no information on the fly

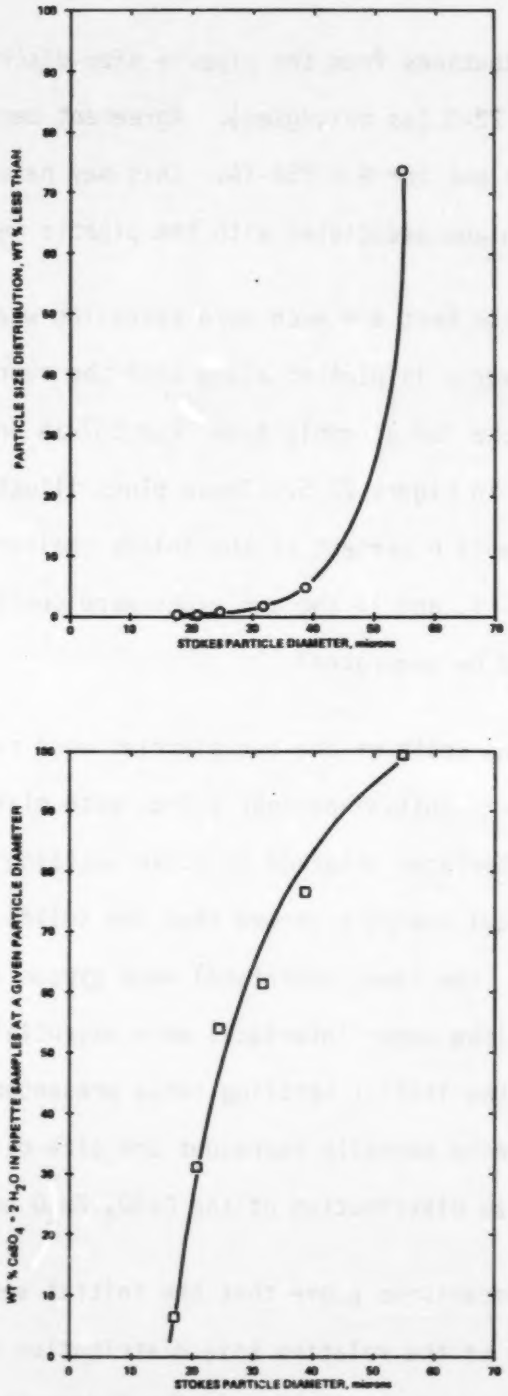


Figure 22-4. Particle Size Distribution by the Pipette Method for Oxidized Slurry with Low Fly Ash Loading from Run 857-1A

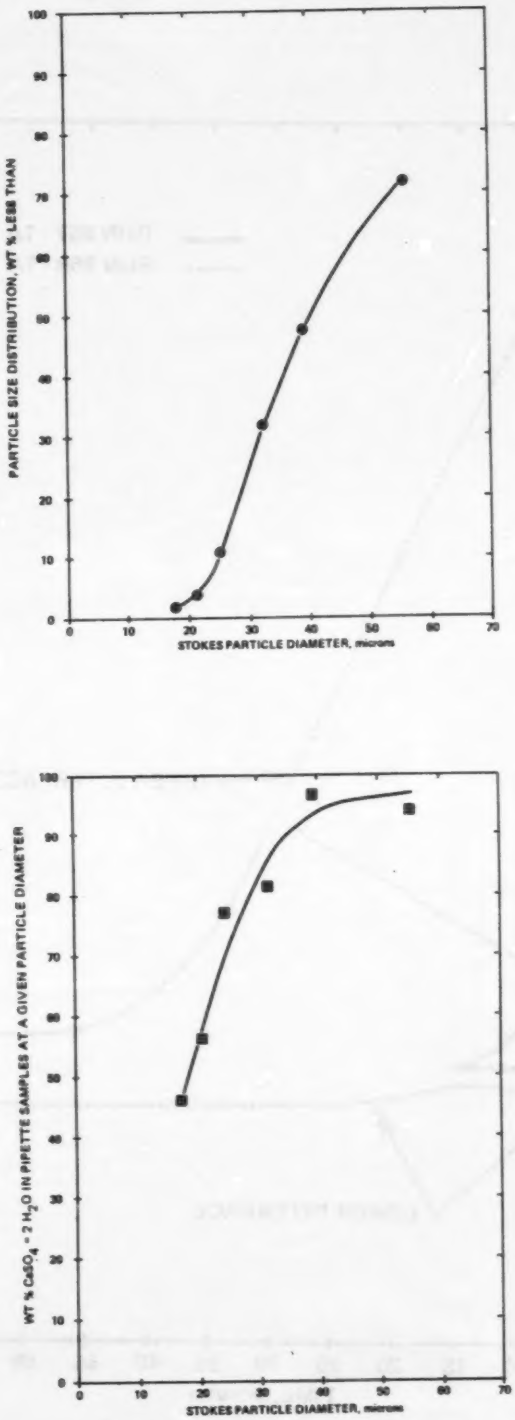


Figure 22-5. Particle Size Distribution by the Pipette Method for Oxidized Slurry with Low Fly Ash Loading from Run 858-1A

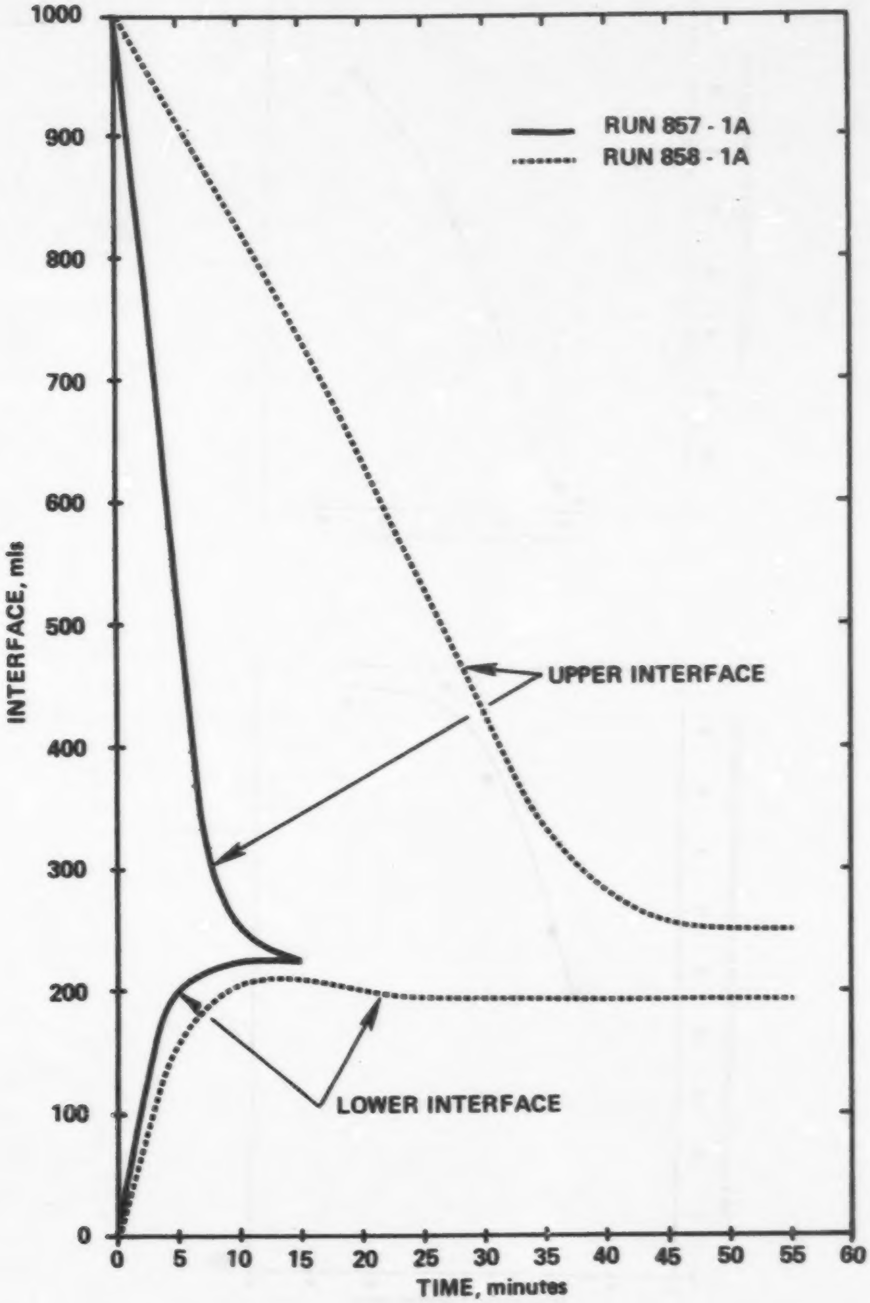


Figure 22-6. Results of Static Cylinder Settling Tests on Oxidized Slurry with Low Fly Ash Loading for Runs 857-1A and 858-1A

ash/gypsum distribution. The pipette method appears to be the most promising method for separating the gypsum size distribution from the fly ash distribution; however, the disagreement between the overall size distribution generated by this method and by the hydrometer method must be resolved before any real confidence can be placed in the results of the pipette test. Further study will be made in the future as time permits.

22.5 HYDROCLONE TESTS

Hydroclones are frequently used for solid-liquid separations because of their small size, low capital cost, and simple design. To determine their applicability as a dewatering device for FGD slurry, a limited test program was conducted at the Shawnee Test Facility in September and November 1977.

The objective of the hydroclone testing was to achieve less than 0.5 weight percent solids in the overflow and greater than 40 weight percent solids in the underflow. Tests were conducted on oxidized limestone slurry from the venturi/spray tower system. The slurry solids consisted primarily of calcium sulfate (30 to 50 microns), fly ash (about 10 microns), and calcium sulfite (about 5 microns). Hydroclone feed was taken from the desupersaturation tank via the discharge of the venturi slurry recirculation pump outlet (see Figure 5-1). Both hydroclone overflow and underflow streams were returned by gravity to the desupersaturation tank.

Tests with a small Doxie 5 hydroclone were discontinued because of plugging; tests with a larger Dorrclone P50A were successful. Underflow solids concentration was excellent (about 55 percent), but overflow solids were high (2 to 3 percent). Chemical analysis showed that 60 to 70 percent of the overflow solids was fly ash.

Based on the limited test results, the hydrometer is judged to be unsuitable as a dewatering device for waste lime/limestone slurry because of high solids content in the overflow. A relatively high energy requirement (high pressure drop) and possible erosion problems would also make it unattractive for this service.

Results of the hydroclone test program are summarized in this section. Detailed test data are presented in Appendix L.

22.5.1 Test Results with the Doxie 5 Hydroclone

The first tests were performed with a Doxie 5 hydroclone manufactured by Dorr-Oliver. The unit consisted of six 10-mm diameter cyclones, and was designed to separate particles as small as 3 to 8 microns in diameter at a pressure drop of 40 psi and a feed flow rate of 5 gpm.

Tests were made with oxidized limestone slurry with low fly ash loading from Runs 815-1A and 816-1A in September 1977. During the first tests, the overflow solids concentration was 0.22 to 0.27 weight percent and the underflow was about 30 weight percent. Pressure drop ranged from 25 to 43 psi, and the feed flow rate ranged from 4.5 to 5.7 gpm. Although the separation was good, the strainer on the Doxie inlet plugged every five to ten minutes. Difficulties with the pump also complicated testing.

A second set of tests was conducted without the strainer. The overflow solids concentration was about 5 weight percent, and the underflow was 25 to 30 weight percent.

These tests indicated that the Doxie 5 hydroclone could separate the small particles but could not handle the large particles also present in the Shawnee slurry. Therefore a larger unit, Dorrclone P50A, with a higher separation size was purchased.

22.5.2 Test Results with the Dorrclone P50A Hydroclone

More extensive testing was done on a Dorrclone P50A porcelain hydroclone manufactured by Dorr-Oliver. The unit had two-inch I.D. feed and overflow connections and a 12-mm (0.47 inch) underflow orifice (1.5 inch connection). It was designed to separate 95 percent of particles greater than 30 microns at a 22 psi pressure drop and a 15 gpm feed rate. A new Moyno pump was used for these tests.

These tests were performed from November 8 to 11, 1977, with oxidized limestone slurry with high fly ash loading from Run 819-1A at a nominal concentration of 15 weight percent solids. Tests were performed to determine the range of pressures and feed flow rates, the flow separation, the solids separation, and the differences in solids composition and size between the overflow and the underflow.

The hydroclone operated a total of 17 hours with no sign of plugging, scaling, or solids buildup. The interior remained smooth and free of erosion.

Several one-half hour tests were conducted to characterize the hydroclone separation. The results of these tests are shown in Table 22-7. Pressure drops ranged from 10 to 29 psi at feed rates of 11 to 19 gpm (maximum for the pump). The outlets were at atmospheric pressure. About 80 percent of the

Table 22-7

RESULTS OF ONE-HALF HOUR TESTS WITH DORRCLONE P50A HYDROCLONE - RANGE OF OPERATION -

Inlet Pressure, psig (= Pressure Drop)	Feed Flow Rate, gpm[1,2]	Overflow Flow Rate		Underflow Flow Rate		Percent Flow Overhead
		gpm[3]	wt% solids	gpm[4]	wt% solids	
10	11	8.8	3.35	2.2	51.27	80
12	12	9.4	3.14	2.6	55.74	78
14	13	10.4	2.41	2.6	49.43	80
17	14	11.0	2.75	3.0	56.66	79
19	15	11.8	2.64	3.2	56.87	79
21	16	12.8	2.36	3.2	54.93	80
24	17	13.8	2.24	3.2	54.55	81
27	18	15.6	1.91	2.4	46.6	87
29	19	16.4	2.08	2.6	53.75	86

1. Measured with a magnetic flow meter.
2. Wt. percent solids was not measured. Values for the venturi inlet line were 15.0 and 16.3 wt. percent.
3. By difference (feed minus underflow). Overflow rate was also measured by bucket but, due to the small size of the bucket, the overflow rate was not felt to be very accurate.
4. Measured by bucket and stopwatch.

total flow went to the overflow. The overflow had 1.9 to 3.4 weight percent solids concentration with higher values at lower pressure drops, as expected. Chemical analyses showed that fly ash was 57 to 62 percent of the overflow solids. The underflow had 47 to 57 weight percent solids at flow rates of 2.2 to 3.2 gpm. Although the underflow solids concentrations were excellent, the overflow solids concentrations greatly exceeded the maximum of 0.5 weight percent desired.

The hydroclone was equipped with an underflow valve that could be throttled to increase underflow percent solids. This valve was not used because the underflow solids concentration was acceptable with the valve fully open.

The overflow was throttled to see whether the overflow solids concentration could be reduced. This increased the pressure drop from 21 to 27 psi at 16.3 gpm feed, but the overflow solids remained at 2.5 weight percent. Fifty-six percent of the total overflow solids was fly ash. The overflow rate was 7.9 gpm. The throttling of overflow diluted the underflow to 26 weight percent solids at a flow rate of 8.4 gpm.

Three two-hour tests conducted at 12, 15, and 18 gpm showed little differences in composition and particle size distributions in the overflow and underflow solids. Operating variables, solids concentrations, and chemical analyses are shown in Appendix L.

The chemical analyses show that the overflow solids were predominantly fly ash (59 to 71 percent) with some gypsum (11 to 13 percent), calcium carbonate (4 to 7 percent), and calcium sulfite (2 to 6 percent).

The underflow solids contained 56 to 58 percent gypsum, 18 to 32 percent fly ash, 5 to 6 percent calcium carbonate, and 1 to 2 percent calcium sulfite. The feed solids were 46 to 48 percent gypsum, 28 to 35 percent fly ash, 5 to 6 percent calcium carbonate, and 1 to 2 percent calcium sulfite. Material balances around the hydroclone show that 80 percent of the flow went into the overflow, but only 12 percent of the solids did. Of the solids, about 30 percent of the fly ash, 23 percent of calcium sulfite, 12 percent of the calcium carbonate, and 3 percent of the gypsum remained in the overflow. The high gypsum separation was a result of its larger particle size.

22.5.3 Particle Size Distribution

Particle size distribution analyses were made by the Bechtel Slurry Laboratory on slurry samples taken from the two-hour Dorrclone P50A hydroclone tests. Overflow and underflow samples were taken at feed rates of 12, 15, and 18 gpm. In addition, the feed was sampled at a flow rate of 15 gpm.

These samples were analyzed by the hydrometer method as described in Subsection 22.4. The Calgon dispersant (sodium hexametaphosphate) normally used in this method was deleted because it reacted with the slurry.

Size distribution analyses for the three feed rates are plotted in Figures 22-7 through 22-9. The plots show that, in the range tested, particle size distributions in the overflow and underflow did not vary with pressure drop and feed rate. The solids size distribution in the underflow was slightly higher than that in the feed. The difference was small because the overflow solids were a minor fraction of feed solids. About 90 percent of the overflow solids were smaller than 15 microns, and about 95 percent were smaller than

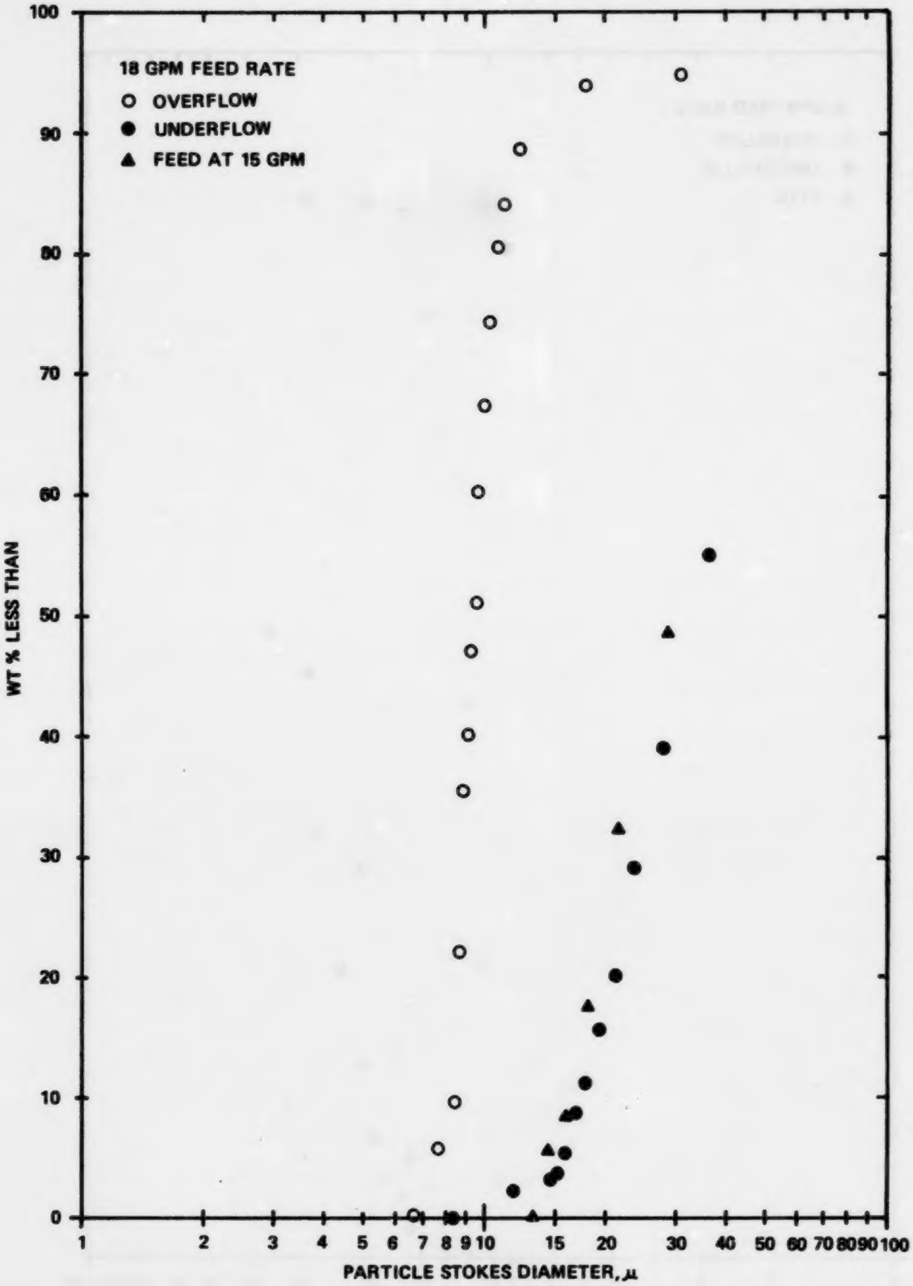


Figure 22-7. Particle Size Distributions from Hydroclone Testing (Dorrclone P50A at 18 gpm Feed Rate and 27 psi Pressure Drop)

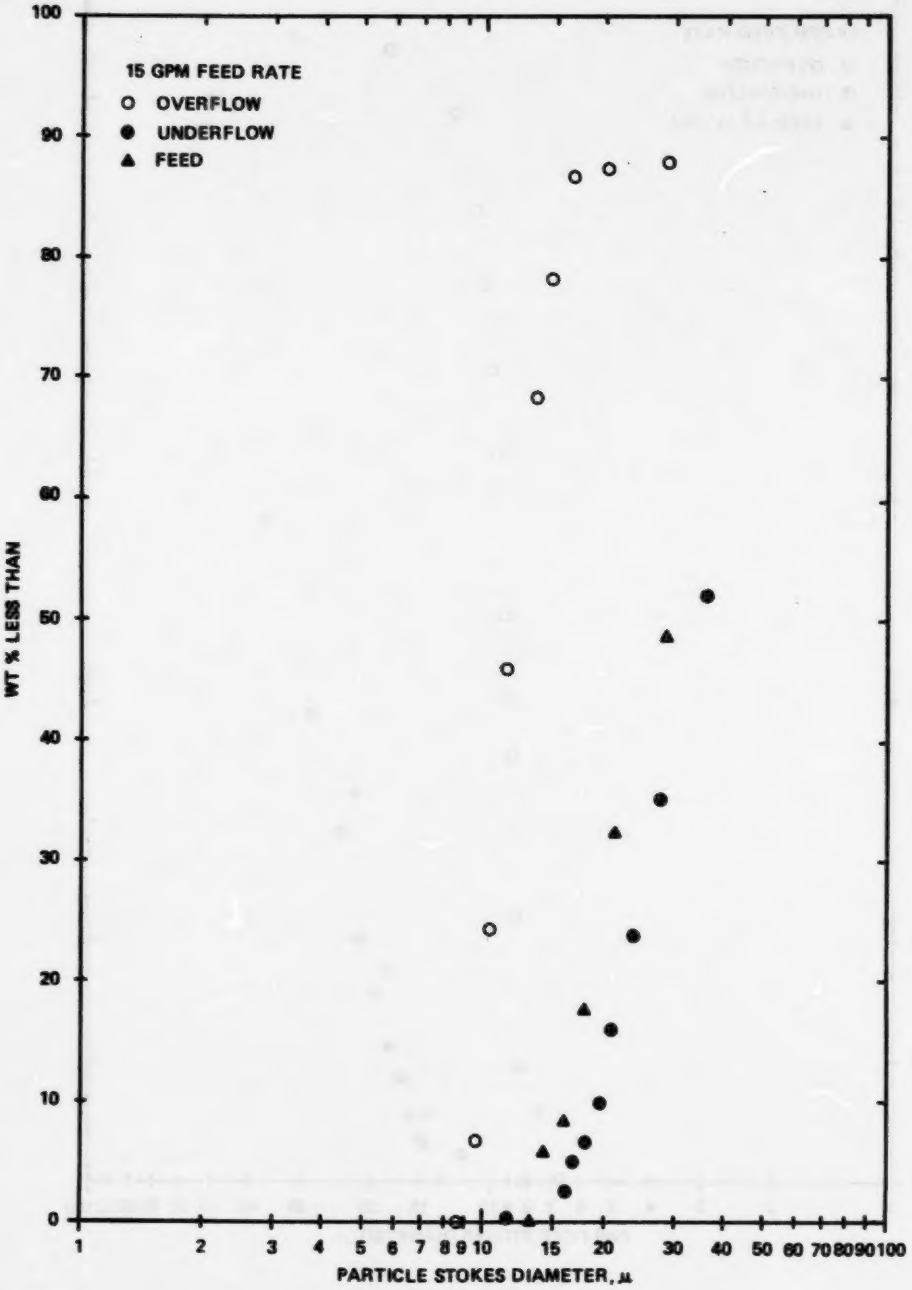


Figure 22-8. Particle Size Distributions from Hydroclone Testing (Dorrclone P50A at 15 gpm Feed Rate and 19 psi Pressure Drop)

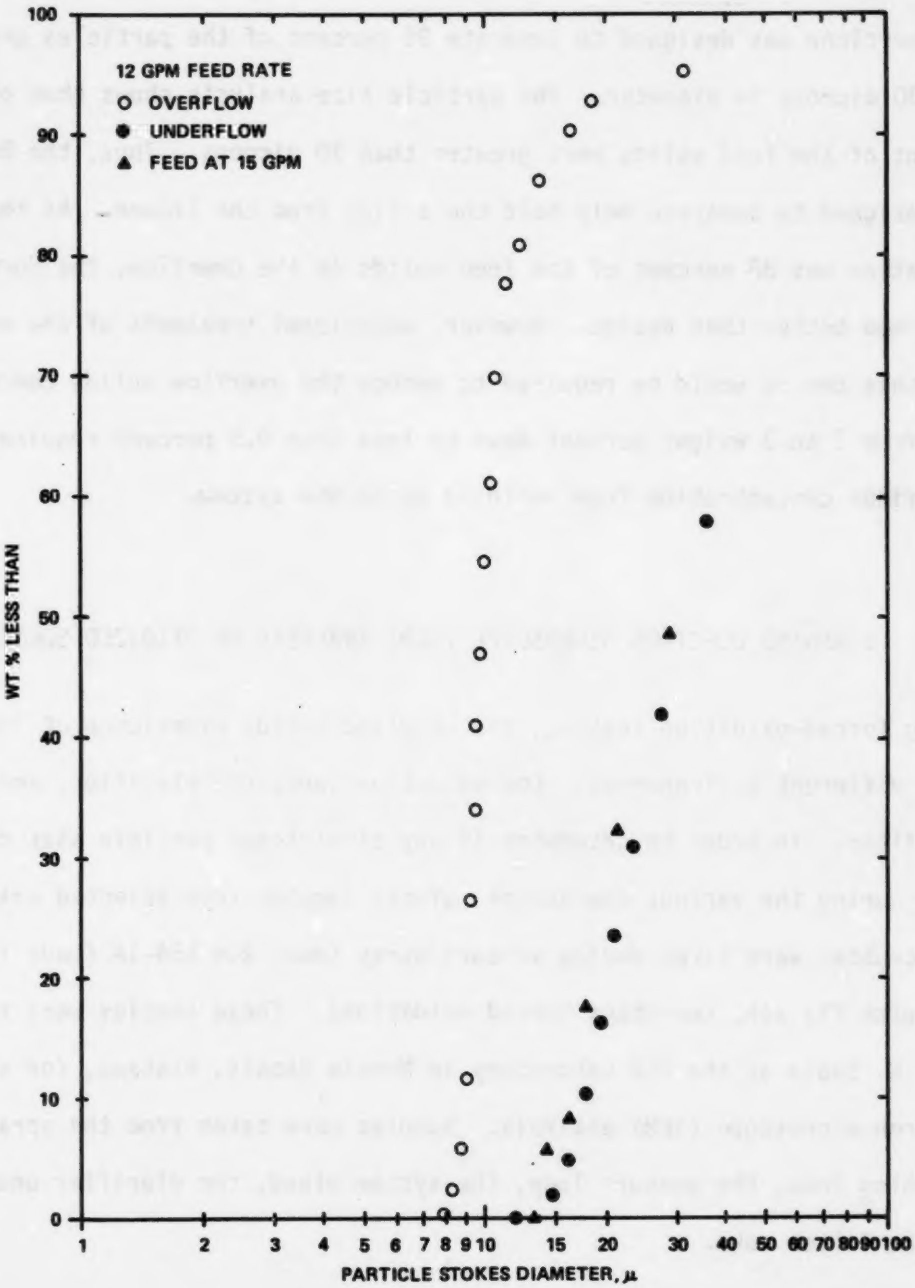


Figure 22-9. Particle Size Distributions from Hydroclone Testing (Dorrclone P50A at 12 gpm Feed Rate and 12 psi Pressure Drop)

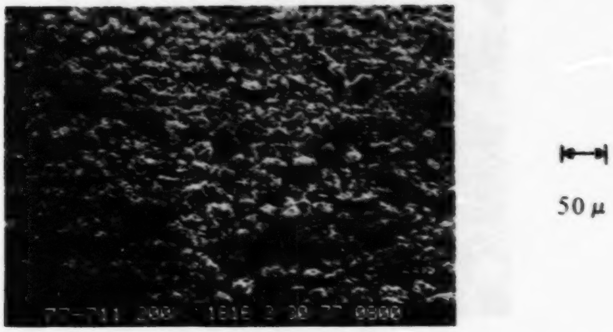
25 microns.

The Dorrclone was designed to separate 95 percent of the particles greater than 30 microns in diameter. The particle size analysis shows that only 50 percent of the feed solids were greater than 30 microns. Thus, the Dorrclone was designed to separate only half the solids from the liquor. As the actual separation was 88 percent of the feed solids in the overflow, the Dorrclone performed better than design. However, additional treatment of the overflow from this device would be required to reduce the overflow solids concentration from 2 to 3 weight percent down to less than 0.5 percent required to keep fines concentration from building up in the system.

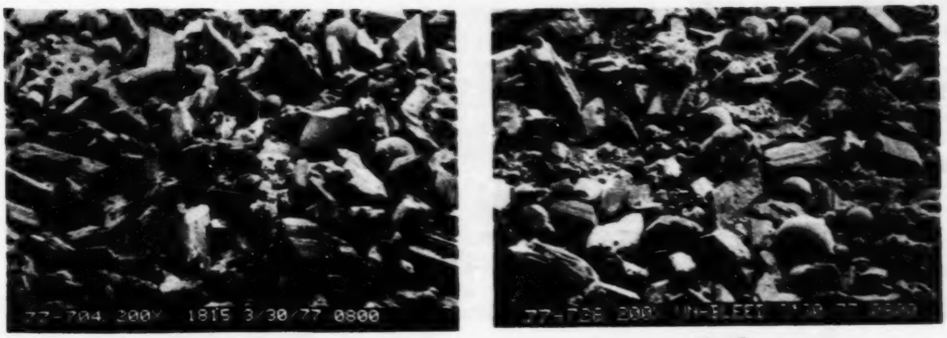
22.6 SCANNING ELECTRON MICROSCOPE (SEM) ANALYSIS OF OXIDIZED SOLIDS

During forced-oxidation testing, the oxidized solids experience at least three different environments: the oxidation tank, the clarifier, and then the filter. In order to determine if any significant particle size changes occur during the various operations, slurry samples from selected points in the scrubber were taken during venturi/spray tower Run 854-1A (made in March 1977 with fly ash, two-stage forced oxidation). These samples were sent to Dr. S.K. Seale at the TVA Laboratory in Muscle Shoals, Alabama, for scanning electron microscope (SEM) analysis. Samples were taken from the spray tower scrubbing loop, the venturi loop, the system bleed, the clarifier underflow, and the filter cake.

Figures 22-10 and 22-11 are SEM photographs of the slurry solids at different magnifications. The solids are 10 percent oxidized in the spray tower loop and 95 percent oxidized at all other points. The crystals from the spray

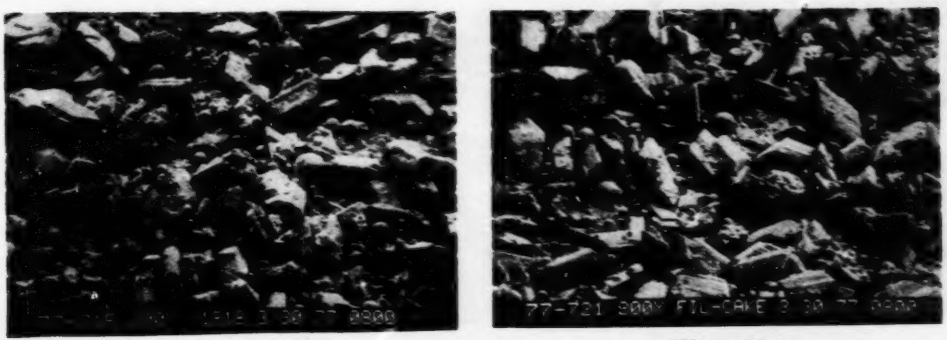

77-711 200X 1816 3 30 77 0800
50 μ

Spray Tower Loop


77-704 200X 1815 3/30/77 0800
77-728 200X UN-BLEED 3 30 77 0800

Venturi Loop

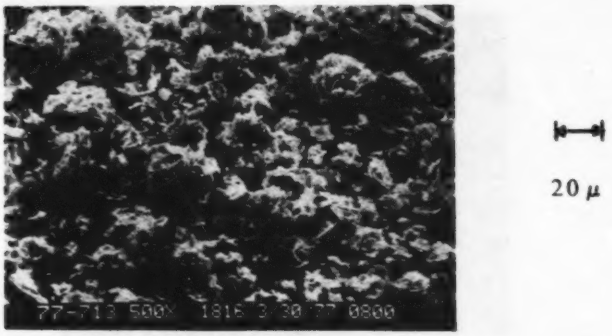
Bleed


1816 3 30 77 0800
77-721 200X FIL-CAKE 3 30 77 0800

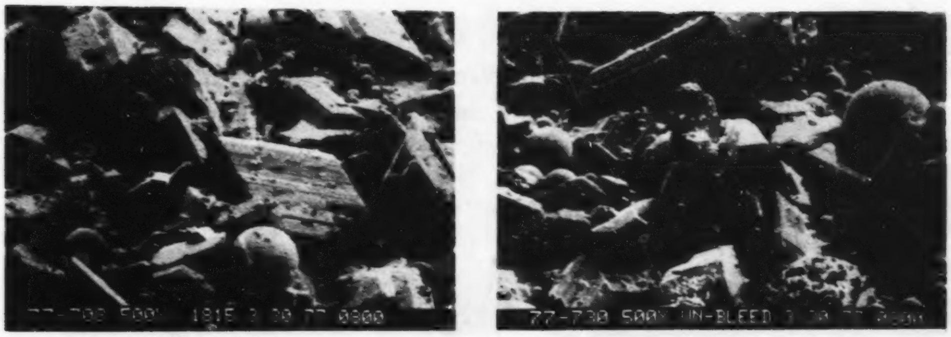
Clarifier Underflow

Filter Cake

Figure 22-10. Scanning Electron Microscope Photographs of Slurry from Forced-Oxidation Run 854-1A (200x magnification)

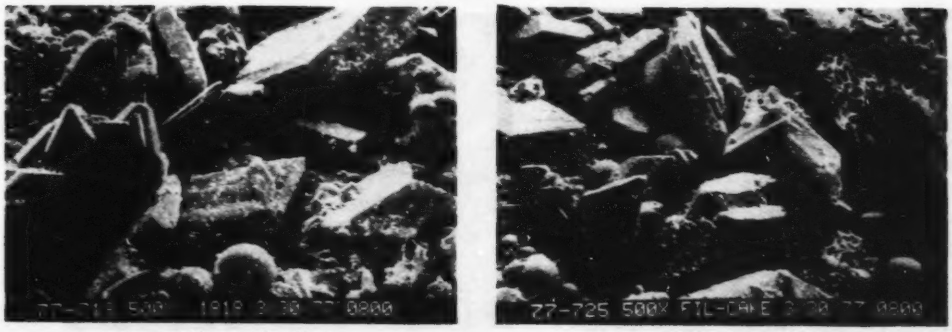

77-713 500X 1816 3 30 77 0800
20 μ

Spray Tower Loop


77-703 500X 1815 3 30 77 0800
77-730 500X UN-BLEED 3 30 77 0800

Venturi Loop

Bleed


500X 1818 3 30 77 0800
77-725 500X FIL-CAKE 3 30 77 0800

Clarifier Underflow

Filter Cake

Figure 22-11. Scanning Electron Microscope Photographs of Slurry from Forced-Oxidation Run 854-1A (500x magnification)

tower loop are primarily calcium sulfite hemihydrate ($CaSO_3 \cdot 1/2H_2O$), while the larger crystals in the other photographs are primarily calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$), and ranged in size from 20 to 100 microns. A comparison of subsequent samples (the bleed, the clarifier underflow, and the filter cake) with samples from the venturi loop indicates that there is no change in the particle size or morphology once the oxidation step has been completed.

22.7 GYPSUM CRYSTALLIZATION

22.7.1 Introduction

Some of the major considerations for any throwaway lime and limestone SO_2 scrubbing process are the ease of waste sludge dewatering and the safe and economical disposal of discharged solids. During the summer of 1977, Dr. J.R. Beckman of California State University, Northridge, investigated gypsum crystallization technology as it applied to the Shawnee flue gas scrubbing systems. This subsection summarizes the results of Dr. Beckman's studies.

Clarification followed by filtration has proved to be a viable method of sludge disposal for the purpose of land disposal. Because of larger interstitial voids, large particles will filter more easily than small particles. Methods that can increase the gypsum crystal size and reduce the number of fines (i.e., improve the solids quality) are therefore desirable.

22.7.2 Theory and Results

The smallest stable crystals capable of growth are called nuclei. There are two ways by which nuclei can form:

- Primary nucleation: the spontaneous clustering of solute molecules into larger stable aggregates in a supersaturated solution.
- Secondary nucleation: the formation of nuclei by crystal-crystal and crystal-solid collisions. This becomes of increasing importance as both turbulence and slurry solids content increase.

To increase the quality of solids, therefore, it is desirable to minimize the number of crystal nuclei in the solution. Both primary and secondary nucleation sources contribute to the total number of nuclei. However, one will usually be dominant for a given system.

According to Dr. Beckman, primary nucleation obeys a "power law" model of the form:

$$n = k_n G^i$$

where:

n = number of nuclei

k_n = constant

G = diameter growth rate of crystals

i = kinetic parameter; constant

Dr. Beckman further states that secondary nucleation is a function of slurry density:

$$n = k_m MT^j$$

where:

k_m = constant

MT = slurry solids content

j = kinetic parameter; constant

The results of modeling show that the quality of solids should improve with increased residence time and/or slurry density if primary nucleation predominates. The opposite should occur if secondary nucleation predominates.

When the solids residence time was halved in the venturi loop, from 15 weight percent in Run 857-1A to 8 percent in Run 858-1A, the final settled solids dropped from 77 to 66 weight percent, and the settling rate dropped from 2.0 to 1.1 cm/min. It should be noted that fly ash interference affects the observation of gypsum settling rate. On the basis of the finding that dewatering becomes more difficult with lowered solids residence time and reduced slurry density, Dr. Beckman concluded that primary nucleation is predominant in the Shawnee system.

Section 23

OPERATING EXPERIENCE DURING LIME/LIMESTONE TESTING

This section summarizes the operating experience during lime/limestone testing, with both high and low fly ash loading in the flue gas and with and without MgO addition at the Shawnee Test Facility from December 1976 through June 1978.

23.1 SCRUBBER INTERNALS

23.1.1 Mist Eliminator Operation

The three-pass, open-vane, chevron mist eliminator, made of type 316L stainless steel, continued in service from December 1976 to June of 1978 on both the venturi/spray tower and the TCA.

From December 1976 to March 1977, moderate plugging was experienced in both systems. Mist eliminator restrictions of 10 to 40 percent* typically occurred after only a few hundred hours of operation. During that time, the wash sequence and spray pattern were continually refined. In February 1977, a continuous underwash system was made available for both the venturi/spray tower and the TCA. Automatic control of the underwash flow was accomplished by an instrument loop, consisting of a magnetic flow meter, controller, recorder, I/P converter (ampere to pressure signal converter), and control valve. By June 1977, the wash sequences and patterns as outlined in Table 23-1 were being used. Since that time plugging has been nearly eliminated.

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* As estimated visually by TVA inspectors.

It was found during the tests that operation at low-alkali stoichiometry made it much easier to keep the mist eliminator clean. Below approximately 1.25 moles Ca/mole SO_2 removed, a periodic flush with fresh water was all that was required. Above a 1.25 stoichiometry, the mist eliminator became progressively more difficult to keep clean, and a continuous wash with diluted clarified liquor was needed.

From June 1977 to June 1978 the venturi/spray tower mist eliminator was cleaned once, in December, after 4183 hours of operation. At that time, the mist eliminator was 15 percent plugged due to a short-term malfunction of the wash system. The venturi/spray tower mist eliminator has operated 3308 hours since that time without plugging; the June 1978 restriction was less than 1 percent.

The TCA mist eliminator was cleaned on June 21, 1978. After 7671 hours of operation, it was only 12 percent restricted.

23.1.2 TCA Grid Supports

The 3/8-inch diameter, 316L stainless steel bar-grids, installed on 1-1/4 inch centers in October 1973, have been in slurry service for approximately 5 years with no evidence of significant erosion. In 1977, two bars in the bottom grid exhibited signs of deterioration. These bars were analyzed and determined

Table 23-1

MIST ELIMINATOR WASH SYSTEM

SCRUBBER SYSTEM	Spray Tower	Spray Tower	TCA	TCA
Gas Flowrate, acfm	35,000	35,000	30,000	30,000
Alkali	Lime	Limestone	Lime	Limestone
Bottomside M.E. Wash				
Wash scheme	LI	C	LI	C
Number of nozzles	10	4	2	2
Nozzle location (inches below M.E.)	10	20	31	31
Size of nozzles(1)	1/2G35W	1/2G35W	1-1/4H190WSQ	3/4HH71WSQ
Nozzle "On" time, min.	6	Cont.	6	Cont.
Nozzle "Off" time	3 hr-54 min.	0	3 hr-54 min.	0
On/Off sequence/nozzle, hrs.	4	-	4	-
Total makeup water, gpm	75	20(3)	75	20(3)
Makeup water/nozzle, gpm	7.5	5.0	37.5	10
Specific washrate (gpm/sq.ft.)	1.5	0.4	1.5	0.4
Δp/nozzle (across each nozzle), psi	50	21	41	20
Wash water (continuous basis), gpm	1.9	-	1.9	-
Topside M.E. Wash				
Wash scheme	LI	HI	LI	HI
Number of nozzles(2)	6	6	6	6
Size of nozzles(1)	3/4H6W	3/4H6W	3/4HH71WSQ	3/4HH71WSQ
Nozzle "On" time, min.	4	3	4	3
Nozzle "Off" time, min.	76	7	76	7
On/off sequence/nozzle, min.	80	10	80	10
Flowrate (gpm/nozzle)	8	8	8	8
Δp/nozzle, psi	13	13	13	13
Covering area (ft^2)	15	15	14.5	14.5
Specific wash rate (gpm/ft^2)	0.53	0.53	0.55	0.55
Wash water (continuous basis)(gpm)	0.4	2.4	0.4	2.4

LI = low intermittent
HI = high intermittent
C = continuous

(1) All nozzles manufactured by Spraying Systems Co.
(2) Sequential wash with one nozzle activated at a time.
(3) Clarified liquor diluted with makeup water.

to be Type 409 stainless steel that were mistakenly installed during a sphere change.

23.1.3 Foam Spheres

During this test period, the three beds of the TCA contained 6-gram nitrile foam spheres obtained from Universal Oil Products. No serious sphere failures occurred during operation. Acceptable levels of initial sphere shrinkage and wear were observed.

Some initial problems did occur because of poor quality control during the manufacturing process. Approximately 10 percent of the nitrile spheres in lot number 6689 contained cuts and splits; these spheres were replaced. Also, in lot number 6874, undersized spheres were present which were small enough to leave the beds by passing through the grids; these spheres were replaced.

From December 1976 to December 1977, the nitrile foam spheres were carefully monitored as to their wear rate. This was done by sampling each bed and measuring the minimum diameter of 25 spheres. Average weight measurements were also made of these samples but were much more variable.

Foam spheres underwent an initial shrinkage*; in the first 1000 hours of service, the minimum diameters decreased by 6 to 12 percent. The subsequent shrinkage rate for the next 6700 hours of service was measured as 0.05 inch per 1000 hours. The average shrinkage rate for the total 7700 hours was 0.07 inch per 1000 hours.

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* Includes decrease in size due to abrasion.

The entire evaluation of sphere wear took place while operating with flue gas with high fly ash loading, which represents a more severe environment than when operating with low fly ash loading. Mixing of the various beds to achieve desired static heights precluded further evaluation of these spheres.

At the completion of Run 820-2A, on January 24, 1978, inspection of the sphere beds revealed that each bed had a quantity of immobilized spheres that were stuck together by scale deposits. The location and number of spheres involved were different for each bed, and was an estimated 5 percent of the bottom bed. This condition had seldom been observed in the TCA and has not occurred since. Gas flow for Run 820-2A was low, 20,000 acfm, equivalent to 8.4 ft/sec, and was the same as the previous run. The spheres in this run had decreased in size, and some of them were forced through the top grid.

23.1.4 TCA Slurry Nozzles

The four main slurry spray nozzles in the TCA were Model 1969F, Type 316 stainless steel nozzles manufactured by Spraco. These continued to give excellent service both in terms of wear and nonclogging characteristics. These nozzles are normally operated at 5 psi pressure drop. Some erosion occurred at the discharge orifice.

23.1.5 Venturi Internals

In January 1977, minor repairs were made to the venturi plug guide vanes and the shroud. Repairs were also made to the rubber lining in the venturi flooded elbow. An inspection of the venturi in March 1977 showed serious abrasion to a section of the guide vane structure that had previously been repaired. The protective rubber covering the four guide vanes had failed to varying degrees and was replaced with new covering. Other maintenance included the replacement of the venturi bull nozzle in December 1977 and the repair of the venturi inlet gas duct in February 1978. Solids or scale deposits in the venturi or the flooded elbow were not a significant problem.

In May 1978, due to a failure of the venturi plug guide vanes, the drive motor was disconnected and a jack was temporarily installed to manually operate the plug. In June, a new venturi plug drive mechanism was fabricated and installed. The shroud splash guard in the plug shaft was rebuilt, a new shaft was fabricated for the plug limit switch mechanism, and new guide vanes and blocks were installed. The old shaft had been in service since March 1972.

23.1.6 Spray Tower Slurry Nozzles

Bete No. ST48FCN nozzles were used successfully as the main slurry spray nozzles in the spray tower. The materials of construction for these nozzles were 316 stainless steel for the body and stellite VI for the spiral diffuser.

New stellite diffusers were installed at the start of Run 801-1A. In March 1977, after a total of 2649 hours, 973 hours of which were in limestone service and 1676 hours in lime service, the diffusers were judged to have negligible pitting and relatively uniform wear, as shown by measured thickness of the reference area of four randomly selected diffusers:

4th level (upper)	0.254 inch
3rd level	0.223 inch
2nd level	0.220 inch

1st level (lower)   0.217 inch

These figures illustrate that flow rates through the four headers were approximately equal, except for a possibly reduced flow rate at the 4th level. The metal used for these diffusers, stellite VI, consisted of 25 percent chromium, 5 percent tungsten, 1 percent carbon, and 69 percent cobalt.

23.1.7 Spray Tower Trapout Funnel

Separation of liquor flow leaving the venturi scrubber from that leaving the spray tower was necessary to achieve independent scrubber loops for the two-loop forced-oxidation testing. This flow division was accomplished by installing a large trapout funnel in the spray tower below the bottom level of the spray nozzles. The funnel and the associated slurry tanks required for the oxidation system are shown in Figure 5-1. Flue gas moves upward around the funnel periphery through the one-foot annular space at the wall of the spray tower and then is deflected over the funnel by an annular ring that is attached to the tower wall. The annular ring also serves to direct falling liquor spray from above into the trapout funnel. There has been no evidence of corrosion on the funnel which is constructed of Type 316L stainless steel.

During normal operation, accumulations of solids on the underside (gas side) of the funnel were a common occurrence. On one occasion, at the end of Run 814-1A, nearly complete plugging occurred on one portion of the funnel. Growth of solids was progressive and built up on the outer edge of the funnel to a point only a few inches from the bottom of the deflector ring. There were no problems with solids accumulation on the inside of the funnel, and no problem was encountered with slurry flow through the downcomer.

As a result of the changes in configuration, there exists an annulus space between the trapout funnel downcomer and the original spray tower slurry outlet, from which a lateral crossover pipe about 50 feet long takes the slurry to the oxidation tank. The annulus and the gravity flow line have been a source of periodic solids restriction. Cleaning of the area normally requires a 2 or 3 man maintenance crew and 3 to 4 hours. The problem has been tolerated because a permanent solution would require unacceptably expensive configurational changes and future testing will allow the elimination of the annulus and the crossover line.

23.2 OXIDIZERS

23.2.1 Air Sparger

The air sparging system used in slurry oxidation involved bubbling air into the bottom of a slurry tank in conjunction with simultaneous slurry agitation. At Shawnee the oxidation tanks were purposely tall and thin (7 to 8 feet in diameter and 20 feet high) to provide a long air/slurry contact time.

The first air sparger consisted of an octagonal ring with 130 1/8-inch holes pointed downward (see Figure 5-2). It was installed near the bottom of the oxidation tank of the venturi/spray tower system in December 1976. During the May 1977 outage, the sparger was inspected after 1745 hours of service. Erosion of the air holes in the ring was noted as follows: 54 holes badly eroded, 33 holes slightly eroded, and 65 holes plugged with hard scale. This sparger was replaced by an identical ring having 40 1/4-inch holes. In October 1977, the new sparge ring was inspected after 2400 hours of operation.

A spool piece connecting the sparge ring to the compressed air source had seriously eroded. It was apparent from the solids in the sparge ring that most of the air had been escaping from the holes in the spool piece for some time. The spool piece material was determined to be Type 304 stainless steel rather than 316L as intended. Despite the nonuniform distribution of air in the oxidation tank, good oxidation was achieved during this test period.

On October 4, 1977, the air sparger ring was removed and replaced with a single 3-inch diameter pipe extending to the center of the tank. Oxidation continued to be good with this arrangement, which indicates that the agitator plays a key role in achieving good air/slurry contact. The air and slurry were mixed with a 20 Hp axial flow agitator rotating at 56 rpm.

During December 1977 the sparger ring with 40 holes of 1/4-inch diameter was installed in the TCA effluent hold tank. The ring, constructed of 316L stainless steel, was materially in good condition, except for minor erosion at the 1/4-inch air holes. A conventional tank agitator (37 rpm, 3 Hp) was used for mixing. Near complete oxidation was achieved with this configuration, but it was suspected that the agitator did not have enough power to achieve good air/slurry contact. Future tests will use a variable speed agitator.

Both venturi/spray tower and TCA sparge systems operated from the same Worthington oil-free air compressor (100 Hp motor) under the following conditions: 50 psig, 270°F, and flow rates normally at 210 scfm per scrubber. The compressor loading/unloading cycle was normally 4 seconds/10 seconds when operating with 210 scfm air flow to the oxidizer. The oil-free compressor was chosen to minimize the possibility of slurry contamination by oil containing oxidation inhibitors.

Maintenance on the sparge systems has been mainly confined to the compressor. During the test period, the following maintenance was performed:

- The compressor would not unload in December 1977. Two of the four loading valves were disconnected, allowing the compressor to operate. The valves were repaired on January 1978 and reconnected.
- In January 1978 the four unloading valves were rebuilt. The Viton O-rings and teflon outer rings were replaced. A compressor discharge air hose ruptured and was replaced.
- The compressor cooling water jacket was back flushed with water in June 1978 to remove scale and silt buildup.

The suction valve was serviced and the compressor cooling water jacket was flushed periodically.

23.2.2 Penberthy Eductor

The eductor is a device that passes a high-velocity slurry through a constricted nozzle, into an eductor chamber, and then through a moderately restricted jet throat. In the chamber, the slurry induces a vacuum that draws ambient air into the chamber via an entry pipe located at right angles to the slurry flow path. The air is then entrapped and mixed in the slurry as the fluid leaves the eductor chamber and passes through the jet throat.

At Shawnee, a Penberthy Model ELL-10 Special eductor was tested. The materials of construction were stellite for the nozzle and neoprene-lined carbon steel for the eductor chamber and exit jet throat. The system was operated at 1600 gpm.

Test results indicated that near complete oxidation could be achieved, but at the same time, serious erosion problems developed. The neoprene lining in the jet throat was observed to be chipped off after only 620 hours of operation. After approximately 1800 hours of operation, bare carbon steel was exposed, and when an epoxy patch failed after a total of 2505 hours of operation, the tests were terminated.

Currently, no plans exist to resume testing of eductors. When compared with sparge air systems, eductors offer no advantages in oxidation capability. Secondary reasons for resuming testing include the materials erosion problem and unfavorable operating and capital costs in comparison to sparge air systems (see Section 12).

23.3 REHEATERS

Flue gas from the scrubber is reheated to prevent condensation and corrosion in the exhaust system, to facilitate analytical sampling, to protect the induced-draft (ID) fans from solid deposits and droplet erosion, and to increase plume buoyancy.

The original in-line, fuel-oil-fired units supplied by Hauck Mfg. Co. were modified in March 1974 (venturi/spray tower) and May 1975 (TCA) to incorporate a fuel-oil-fired external combustion chamber manufactured by Bloom Engineering Co. Both units have operated reliably since the modifications, with only occasional flameout and equipment problems. During the test period, maintenance consisted of the following:

- The venturi/spray tower Honeywell oil controller failed in February 1977, and was replaced.
- The motor on the TCA reheater combustion air blower was replaced in June 1977.

- The venturi/spray tower reheater control failed in September 1977, due to a faulty UV fire eye, and was replaced. During the same month, the TCA reheater air control failed due to a faulty interlock relay and was replaced.
- The TCA Bloom reheater UV fire eye malfunctioned and was replaced in February 1978. The venturi system Bloom reheater ignitor was completely rebuilt.
- The TCA reheater oil flow transmitter, detector, and eccentric beam failed in April 1978. The transmitter circuit was modified to utilize a 10- to 50-milliamp, 75-volt transmitter, and the system was returned to service.
- The TCA oil flow control valve failed in May 1978 and was removed, completely cleaned, reset to factory specifications, and reinstalled. The valve was worn and pitted.
- The TCA oil flow transmitter, which failed in April, was replaced.
- The ignitor for the venturi/spray tower reheater failed and was replaced in May 1978.

During the test period, accumulation of dried slurry solids in and around the reheater was common. Typically, gas ducts to the Hauck reheater shell gained in buildup of scale close to the reheater entrance and developed a buildup within the shell that extended upwards to the discharge of the Bloom reheater. Other deposits occurred above the Bloom discharge and in the discharge duct from the reheater. The solids were allowed to accumulate to a thickness that would cause a significant pressure drop increase across the length of the duct. At that point the solids were manually removed. Cleaning was required about once every two months.

23.4 FANS

The 316L stainless steel fans at the Shawnee Test Facility are ID, centrifuge fans manufactured by Zurn Industries. Reliability has been fair to good during the current operating period, with the only system downtime due to the following fan problems:

- Occasional cleaning of the fan and fan dampers
- Replacement of the ID fan outboard bearing and pillow block, five times for the two fans during the last 18 months
- Replacement of the motor on the Beck damper position control

23.5 PUMPS

23.5.1 Allen-Sherman-Hoff Pumps

The Allen-Sherman-Hoff centrifugal pumps are neoprene lined, slurry service pumps equipped with Nelson liquid drive units. The pump packing that is used consists of conventional graphite-impregnated asbestos, the sleeves are 316 stainless steel, and the pump seals are of the air-flush type (centriseal) used to prevent excess water input to the circulating slurry.

Considering the wide range of operating conditions, the pumps provided satisfactory service with a moderate maintenance requirement. Table 23-2 shows a tabulation of pump maintenance during the test period. The most frequent reason for maintenance was repacking. Although there was no apparent pattern associated with repacking frequency, the following general trends were observed:

- Wide flow variation as dictated by changing test conditions increased repacking frequency.
- Operation of a pump at the low-flow end of the pump curve accelerated the frequency of packing problems.

23.5.2 Moyno Pumps

Moyno pumps are positive displacement variable-speed pumps used principally

Table 23-2

FREQUENCY OF PUMP MAINTENANCE

Equipment Number	Name (Capacity, gpm)	Repacked	Replaced										Vari-drive Oil Change	Oil Cooler Modified or Cleaned	Water Seals Repaired	Couplings Repaired	Other
			Shaft	Sleeve	Belts	Bearings	Suction-side Liner	Drive-side Liner	Impeller	Barrels	Stators	Oil Coolers					
G-101	Main Slurry (650)	3		1	2	1		1	1			1	1	1			
G-102	Thickener Underflow (50)	14		3	1									2	2		
G-103	Process Water (650)	1				1								2			
G-104	Main Slurry (650)	3			2	1	3	2	1					1	1		
G-105	Bleed (100)	4		3			2	1	1			1					
G-107	Mist Eliminator Wash (40)	2*													1	1	Replaced I-R with Durco Mark II
G-108	Alkali Addition (8)	6	1	1						8	7						Replaced Vari-drive
G-109	Bleed (100)	34		3			1								1		
G-201	Main Slurry (1200)	17		1	1			1	1			1					Bad motor ground repaired
G-202	Thickener Underflow (50)	10		2	1	1									3		
G-203	Process Water (650)	2										1					
G-204	Main Slurry (1200)	57		3		1	1	1	1			1		1			
G-205	Bleed (100)	2*					3								2		
G-207	Mist Eliminator Wash (40)	1*				1											
G-208	Alkali Addition (8)	19			4					2							
G-203A	Process Water (100)	1*		1													Replaced coupling
G-202A	Thickener Underflow (50)	1	1			1				1	1						
G-401	Sludge-to-Waste (850)	1										1					
G-408	Centrifuge Cake Reslurry (35)	2		2	2										1		
G-409	Centrate Return (50)														2		
G-410	Filtrate Return (50)	4	1	1	1										1		Replaced with Durco Series E
G-412	Filter Cake Reslurry (35)	1		1													
G-502A	Service Water (400)	2															
G-502B	Service Water (400)	3														1	
G-501A	Fuel Oil					1											
G-501B	Fuel Oil	1*				1											

* Replaced mechanical seal

for supplying alkali makeup slurry for the scrubbers. Five such pumps located near the alkali storage tanks served this purpose. A larger sized Moyno is used for the recirculation of underflow from the TCA clarifier. This pump has seen only limited service.

Moyno pump rotors are helical shaped and made of chrome plate steel for abrasion resistance. Stators are rubber-lined with a double helical groove. The most frequent maintenance problem associated with these pumps is the replacement of eroded pump stators. Occasionally, there was a loss of pump capacity resulting from erosion of the rotor surface after what appeared to be a failure of the chrome plating.

23.6 ALKALI ADDITION SYSTEMS

23.6.1 Lime

The lime addition system consisted of a storage silo, a screw feeder, a lime slaker manufactured by Portec-Cahaba, a slaked-lime holding tank, and associated feed pumps. Fresh water slaked the lime to approximately 20 weight percent solids. The system gave good reliability over the last 18 months of intermittent operation.

Maintenance consisted principally of periodic slaker cleaning and the replacement of the slaker grit screen on seven occasions. In February 1978, in addition to a screen replacement, the screen shaker motor, drive shaft and bearings were replaced. The slaker process control elements were cleaned and serviced in March 1978.

23.6.2 Limestone

The limestone addition system consists of a drying-grinding system, a dry storage tank, a weigh belt feeder, a slurry tank, and an associated feed pump. The dry-grinding system was installed in 1970 for a dry limestone injection project which preceded the present program. Considering the age of the system, it has given acceptable performance with moderate maintenance requirements during this test period. The following significant maintenance was performed:

- The expanded metal and refactory was replaced in two-thirds of the barrel in the burner section of the limestone dryer (April 1977).
- The limestone ball feeder circuit was repaired, and the magnetic starter for the limestone feed belt motor was replaced (July 1977).
- The limestone grinding system dryer was restored to its original condition after a section of refractory had fallen loose and a portion of the inner liner had melted (October 1977).
- The refractory in the burner section of the limestone grinding system dryer was patched several times. The initial patching with rock wool insulating cement proved unsuccessful. "Krocrete B" refractory was used for subsequent repairs (November 1977).
- The fuel oil controller on the limestone grinding system dryer was replaced because equipment vibration was causing breaks in the circuit boards. A new controller with a more vibration resistant mounting was installed (February 1978).
- New Honeywell operating controls on the limestone grinding system dryer and new gauges in the fuel oil and atomizing air lines were installed (March 1978).

23.7 DEWATERING SYSTEMS

The primary dewatering of the purged slurry in both scrubbers was achieved by clarifiers. Further dewatering of the clarifier sludges was accomplished in the venturi/spray tower system by a filter and in the TCA system by a centrifuge.

23.7.1 Filter

An Ametek 3 ft x 6 ft rotary drum vacuum filter without cake wash was operated at the facility for waste sludge dewatering and dissolved scrubbing additive recovery. Cake discharge was effectively achieved by a snap-blowback cycle. In December 1976, a variable speed drive was installed on the drum.

The feed to the filter was typically 15 gpm with 30 to 40 weight percent solids content. The filtrate generally contained less than 0.02 weight percent solids. The filter cake varied from 55 to 85 weight percent solids, depending mainly on whether the sludge was unoxidized or oxidized.

With the exception of the filter cloth, the filter was a moderate maintenance item. Table 23-3 gives a breakdown of maintenance categories, frequency, approximate total manhours required, and approximate material costs.

Filter cloth replacement, as noted in Table 23-4, was a serious problem at Shawnee. The causes of cloth blinding and fraying were not completely understood. However operating experience indicated a relationship between cloth life and the technique by which the cloth was fitted to the drum. A certain amount of looseness in the fit between the dividers appeared to be desirable for cake discharge and nonblinding. For this filter the looseness was approximately 1-1/2 inches of extra cloth per filtration section (10 inches x 6 feet section). After being in service for a few hundred hours the cloth shrunk to approximately 3/4-inch of looseness per section. A three-man maintenance crew was used to change the cloth; one hammered in the rope caulking while the other two workers folded over and held the desired looseness of the cloth. The looseness evidently allowed the cloth to snap the cake off when the air puff of the cake discharge cycle was applied to

Table 23-3

FILTER MAINTENANCE REQUIREMENT
December 1976 to May 1978

Event	Frequency of Occurrence	Estimated Total Onsite Labor (man-hours)	Estimated Total Material Cost ($)
Drum Speed Control Repair	3	24	1000
Snap Blowback Repair	2	16	0
Cloth Replacement	15	90	1500

Table 23-4

FILTER CLOTH SERVICE

CLOTH TYPE*	DATE INSTALLED	HOURS IN SERVICE	COMMENT
1. Ametek	11/8/76	1721	Blinded
2. TFI	6/6/77	292	Blinded
3. Lamports	7/7/77	127	Hole in Cloth
4. Lamports	7/13/77	142	Blinded
5. Lamports	7/19/77	302	Blinded
6. Lamports	8/3/77	249	Blinded
7. Lamports	8/15/77	540	Blinded
8. TFI	9/19/77	187	Blinded
9. TFI	9/23/77	501	Blinded
10. Lamports	10/18/77	187	Blinded
11. Ametek	10/28/77	2096	Hole in Cloth
12. Ametek	2/8/78	188	Blinded
13. Lamports	2/14/78	190	Hole in Cloth
14. Lamports	2/22/78	290	Blinded
15. Ametek	3/21/78	535	Blinded
16. Ametek	4/19/78	1197	Hole in Cloth

* Ametek - Ametek olefin (STE-F9D8-HJO)
Lamports - Lamports Polypropylene (7512-SHS)
TFI - Technical Fabricators Incorporate, Polypropylene (9162)

the given filter cloth section. The oxidized sludge exhibited less tendency towards cloth blinding, and the Ametek olefin appeared to provide the most satisfactory service of these cloths tested. The better service life of Ametek was tentatively attributed to the looseness of the Ametek weave in comparison with the Lamports and TFI weaves.

23.7.2 Centrifuge

A continuous centrifuge is used to dewater scrubber waste sludge from the TCA system and to recover the dissolved scrubbing additives. Typical operating conditions consisted of a feed stream flow of 15 gpm at 30 to 40 weight percent solids, a centrate of 0.1 to 3.0 weight percent solids, and a cake of 55 to 65 weight percent solids for unoxidized slurry and 70 to 80 weight percent for oxidized slurry. Approximately 40 percent of the total solids was fly ash; the remaining solids were predominantly calcium sulfate and sulfite.

The machine is a Bird 18 inch x 28 inch solid bowl continuous centrifuge which operated at 2050 rpm. The material of construction is 316L stainless steel with stellite hardfacing on the feed ports, conveyor tips, and solids discharge ports. The bowl head plows and case plows are replaceable. The pool depth was set at 1-1/2 inches. No cake washing was performed in this machine.

In January 1977, vibration readings were taken on the Bird centrifuge with the lapse timer reading 5711 hours. The previous set of readings was taken on June 23, 1976, when the timer reading was 2126 hours. The results, shown in Table 23-5, indicate that the vibration had increased slightly.

Table 23-5
CENTRIFUGE VIBRATION MEASUREMENTS

		Maximum Vibration, mils	
		2126 Hours	5711 Hours
Centrifuge:	Inboard bearing, horizontal	5.0	3.8
	Inboard bearing, vertical	3.0	4.2
	Outboard bearing, horizontal	8.2	9.5
	Outboard bearing, vertical	5.5	8.5
Motor:	Drive end, horizontal	2.5	4.6
	Drive end, vertical	6.0	10.0
	Inboard end, horizontal	3.2	5.0
	Inboard end, vertical	1.8	3.5

The centrifuge was disassembled on March 22, 1977, for inspection. Major wear sites were found at the two center feed ports at the periphery of the screw conveyor, and at the plows on the solids discharge end. Limited stellite hardface welding was performed onsite. Approximately 4000 hours of operation had been logged on the centrifuge since the machine was last serviced by Bird.

The Bird centrifuge was dismantled and inspected, and the feed pipe was replaced in March 1978. In June, the centrifuge was inspected after 6460 hours of operation since the previous servicing. The inspection was prompted by the gradual and continued increase of centrate suspended solids to a level of approximately 3 weight percent. The machine was judged to be in generally fair condition, but certain components were in need of factory repair. Serious wear was observed at the conveyor tips on the discharge end and at the junction of the cylinder and the 10 degree section of the conveyor. Wear was also present at the casing head plows and solids discharge head near the discharge ports. The bowl and effluent head were in good condition.

The centrifuge will be shipped to the factory in July 1978 for an overhaul that will include servicing the gear and bearing unit, rebuilding all worn conveyor surfaces and discharge parts, adding hardfacing to the conveyor tips and discharge ports, and replacing all seals, bushings, case plows, and discharge plows as necessary.

In an attempt to improve performance and machine life, tungsten carbide hardfacing will be applied to the conveyor tips, instead of the previously used stellite.

23.8 INSTRUMENT OPERATING EXPERIENCE

23.8.1 pH Meters

The process pH is monitored using Uniloc Model 321 submersible electrode assemblies. Originally, Uniloc Model 320 flow-through meters were installed. But because of line plugging problems and frequent sensing electrode breakage, this type of sensor was abandoned. Service requirements for the submersible assemblies consisted of periodic cleaning and buffering of the electrodes, generally every 2 or 3 days to ensure accuracy. Also to minimize the service requirement, the instrument electrodes were placed in water when the scrubbers were not operating. On infrequent occasions, the electrode assembly failed due to wet electrical contacts, bad reference, or sensing electrodes. To prevent disruption of online pH monitoring, spare electrode assemblies were maintained in standby at all times.

To ensure the accuracy of the process pH meters, a procedure was established in which a laboratory-measured pH was taken once every two hours for comparison purposes. This procedure permits a normal operation to within ± 0.2 pH unit of a desired set point, a basic requirement for obtaining accurate test data at the Shawnee Test Facility.

23.8.2 SO_2 Analyzers

A Du Pont Model 400 UV split-beam photometer is used to measure SO_2 concentrations. In the last 18 months, the instrument was accurate and reasonably trouble-free. Maintenance requirements were limited to cleaning the sample cell and sample lines approximately once every 1 or 2 months and cleaning the particulate filter about once every 3 to 4 weeks. Ultraviolet lamp failure was the only component problem and was caused by uncontrollable and momentary power fluctuations due to the switching of station power. The effective particulate filter for the instrument at Shawnee was a cylindrical chamber constructed of a fine mesh screen. The screen cylinder was surrounded by a solid open-ended protective cylinder. The gas sample lines operated leak free; the lines were Teflon tubing with heat tracing.

23.8.3 O_2 Analyzers

Oxygen in the inlet flue gas was measured with a Teledyne Model 9500 which used a microfuel cell. Operating performance was not acceptable because of the following reasons:

- The Teledyne oxygen analyzer system was put into service on June 15, 1977, and worked properly until June 21 when the sequence mechanism failed.
- The sequence mechanism was serviced and reinstalled on July 11, but on July 13 the fuel cell failed.
- The analyzer with a new cell was put into service on August 22, and on August 23 the sequence mechanism failed for the second time.
- On October 11 through 13, several resistors were replaced, and the system was calibrated against a portable Teledyne analyzer. On October 17, the fuel cell failed and was replaced.
- The system was disassembled and cleaned on November 18. The solenoid valves were scaled and inoperative. On November 27, the fuel cell failed and was replaced.
- In December, the solenoid valves failed on the inlet sample system. The fuel cell failed on December 21 and was replaced.
- The analyzer was inoperative most of January because of freezing problems with the instrument scrubbing water supply.
- Two fuel cells failed in March. The water scrubbing system plugged with rust particles and was cleaned on March 17 and again on March 20. A filter was installed in the water supply line on March 29.

- The fuel cell failed on June 13 after 30 days of operation, and a new cell was installed.

23.8.4 NO_2 Analyzer

In December 1976, a Du Pont Model 400 UV photometer was modified by Du Pont technicians to analyze for NO_2. The system was initially installed at the TCA inlet. For the duration of the tests, which lasted until February 1978, no useful data were obtained due to the erratic output signal. Numerous modifications and checks were performed by Du Pont representatives, but the source of the problem was not located. The test was judged to be a failure. Further testing was discontinued in consideration of cost and interest.

23.8.5 Magnetic Flowmeters

During the past test period, the Foxboro 2800 series and 1800 series magnetic flowmeters were used exclusively and showed no serious problems. Scale cleaning was required to improve accuracy and sensitivity, and on infrequent occasions the magnetic converter required maintenance. Nearly all meters are equipped with electric purge systems for scale removal. The system worked satisfactorily except for a few meters that required periodic manual/chemical scale cleaning. The most frequent cleaning was required on the bleed meters and alkali addition meters. The frequency was approximately once every six weeks and was normally performed at a convenient opportunity, e.g., the boiler was off-line. Cleaning was accomplished by a HCl acid wash and manual scraping of the electrode button with a soft wood stick. On large meters where a man's hand can be inserted, fine sandpaper was used to remove tenacious scale.

The electronic components of the meter have worked well. Of all the meters at the test facility perhaps three per year need to have relay contacts cleaned or repaired. However, the meters were considered reliable, acceptably accurate, and relatively easy to service.

23.8.6 Density Meters

Both Dynatrol Model CL-10HY U-tube density meters and Ohmart radiation density meters are used at Shawnee. Both types of meters provided acceptably accurate and dependable service. The instruments were most useful in monitoring trends in density. From an operations point of view, the U-tube meters had some initial problems with line plugging. The cause was attributed to operator error in setting too low a flow through the instrument. The appropriate corrective measures consisted of manually setting the flow through the instrument at 8 gpm. Care was taken to avoid high flow setting because the U-tube would erode and fail.

23.9 MATERIALS AND EQUIPMENT EVALUATION

During the test period, the following equipment/materials were monitored:

- Lining and piping
- Control valves
- Strainers

23.9.1 Lining and Piping

23.9.1.1 TCA tower lining

Hardness measurements were made of the tower lining in March 1977. Measurements were made in areas in contact with spheres or areas receiving direct spray impingement. The range of readings was 44 to 57 Durometer which corresponds closely to the readings published in the Third Interim Report on Corrosion Studies (Reference 3, Appendix L). Generally, the lining was in good condition although the surface where scale was often removed exhibited scabs from chipping tools. There was no evidence of rubber lining separation from the metal shell.

23.9.1.2 PVC pipe

A number of system modifications required the installation of plastic piping. Schedule 80 PVC 1120 (ASTM D-1785) piping of 6- and 8-inch sizes was installed for a large section of the main slurry line for the TCA. Fittings were all of standard radius design. PVC piping also served the venturi/spray tower oxidation tank system. The operation of the PVC piping was satisfactory from a mechanical standpoint.

23.9.1.3 Rubber-Lined pipe

During the March 1977 boiler outage, blisters were observed in some sections of the rubber-lined pipe. To date, these blisters have not precipitated pipe failures or blockage problems and therefore do not pose an operating or maintenance problem at this time.

23.9.1.4 Pullman Kellogg Test Panel

A test panel (20 inches x 15 inches x 3/8 inch) supplied by Pullman Kellogg and made of carbon steel coated with fluoroelastomer CXL-2000 was installed in the inlet gas duct of the TCA scrubber before the start of Run 705-2A in January 1977. It was arranged to have cooling slurry spray impinge across the panel face. Inspection of the panel on May 2 showed that the coating had failed along the exposed flanged edge allowing erosion of the carbon steel substrate. The panel had been exposed for approximately 2000 hours of service. The panel was removed; the material was judged to be unsatisfactory in this particular service and no further testing was planned.

23.9.1.5 Test Pipe - Bondstrand

A section of U-shaped Bondstrand fiberglass-reinforced plastic pipe was removed from service in March 1977. It had been installed in the suction line of the TCA main slurry pump. The estimated total service period for the pipe was approximately 8800 hours. There did not appear to be any significant wear of the pipe surface, and the entire section was considered to be in excellent condition.

23.9.2 Control Valves

23.9.2.1 Valtek 6-inch butterfly control valve

Since the inspection of September 1976, further erosion had taken place in the body of this valve. Previously observed grooves had deepened, and the worst single hole located in the disk plane was 0.28 inch deep. Measurements at the outer edge of the stellite disk ranged from 0.22 to 0.24 inch. The valve was judged conditionally acceptable for slurry service; the valve disc does wear and will need replacement eventually.

23.9.2.2 Fisner 2-inch butterfly control valve

This valve had a fishtail disk which was judged to be in excellent condition. Erosion had caused only slight rounding of sharp edges of the disk and pitting. Minor erosion had also taken place in the body of the valve in the plane of the closed disk position. The estimated maximum depth of wear was 0.5 mm. The valve body appeared to be wearing faster than the disk in the throttling service. During March 1977, the valve was moved from the venturi/spray tower to the TCA.

23.9.2.3 Durco 6-inch butterfly valve

Located in the venturi/spray tower, this valve was considered to be in excellent condition, except for four small irregular wear patterns at the disk edge possibly caused by debris trapped at the sealing edge during closure. The valve body liner of abrasive-resistant polyethylene was in excellent condition. Measurements of the disk thickness showed no change or loss of the coating material. The valve service was primarily in the open position.

23.9.3 Strainers

Hayward strainers in both systems were inspected in November 1977. The 8-inch size strainers on the TCA showed erosion at the basket support ledge and at the lower half of the strainer outlet. Similar erosion occurred in the 6-inch size strainer used on the venturi/spray tower.

Elliott strainers located in the main slurry line to the venturi/spray tower were one of the two original sets. There did not appear to be further erosion of the strainer body at the flange locations where this type strainer had previously leaked.

All the strainers required infrequent maintenance (once or twice per year) that consisted of basket replacement (most frequent) and bead-welding of the eroded basket support ledges. The strainers were judged to be very useful and well worth the cost from the standpoint of preventing scale/solids accumulations in the spray nozzles.

23.9.4 Corrosion Studies

The Fifth Interim Report on Corrosion Studies at the test facility, written by TVA, is presented in Appendix K. The report covers the operating period from October 1976 through February 1978 and discusses corrosion and erosion of the test facility equipment and test specimens.

Section 24

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